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PRIORITIZING ELECTROMAGNETIC INTERFERENCE TESTING OF DEVICES USED IN UNDERGROUND COAL MINES

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ABSTRACT

Electrical devices and equipment used in underground coal mining produce and may also be susceptible to electromagnetic energy. This energy can sometimes create nuisance interference or even impact the performance of equipment to the extent of becoming a hazard. This paper describes how a failure mode and effects analysis (FMEA) was employed to assign priority for evaluating electromagnetic interference (EMI) and electromagnetic compatibility (EMC) among devices and equipment used in underground coal mining. An overview of the process used to determine ratings for severity, occurrence, and detection is provided along with corresponding results concerning risk and criticality. The information presented in this paper can be used to evaluate risk profiles where the extent of a problem may not be well understood, and limited information is available regarding potential failure events. The research method presented can be applied to identify equipment to test and to aid in the potential development of mitigation strategies to overcome electromagnetic interference challenges encountered in mines.

INTRODUCTION

In 2006, the U.S. Congress passed the MINER Act [1]. This legislation marked a distinct change in health and safety regulations for underground coal mines in the United States and provided a path for new technology, including wireless communication and electronic tracking systems. Soon after, other technology entered the industry through additional regulations, including magnetic proximity detection systems on continuous miners and personal dust monitors to measure mine worker exposures.

As the use of electronic safety systems and devices, such as those for communication and tracking, proximity detection, and sampling, have become more prevalent in mining, understanding electromagnetic interference (EMI) and electromagnetic compatibility (EMC) are becoming progressively critical to the safety and health of miners. Electromagnetic energy produced by electrical equipment and electronic devices can cause nuisance interference affecting susceptible devices, even to the extent of becoming a hazard. For example, the personal dust monitor is known to emit constant electromagnetic energy that can cause potentially hazardous situations by interfering with the miner-wearable component or personal alarm device of proximity detection systems (PDSs) used in underground coal mining [2].

In the United States, coal regulations require explicit electronic devices that must be carried by certain mine workers at all times underground. For example, almost all miners use cap lamps with battery-powered electronics [3]. There are also other electronic devices that miners commonly carry to complete their shift. One example is a personal gas monitor which can quickly and continuously monitor the mine atmosphere for harmful gases or lack of oxygen in the air. These devices, while not required to be carried by a miner at all times, are used in underground coal mines to conduct required ventilation examinations. Regulations as well as individual mine characteristics can greatly affect the likelihood that a device would be present and affected by other electronic devices.

The National Institute for Occupational Safety and Health (NIOSH) Mining Research Program is focused on identifying the potential for EMI in underground coal mining, assessing the associated risk, and developing mitigation strategies. In 2019, a research project was initiated to focus on understanding and addressing interference between electrical and electronic devices used in mines [4]. The proposed research called for a risk analysis to identify high-risk EMI-related devices as well as potential mitigation strategies for addressing the associated interference. Ideally, information gained through this research effort will be used to develop mining-specific recommendations for furthering EMC in mining environments. For the study presented in this paper, the primary goal is to identify categories of devices having a high-risk potential for EMI-related events.

The International Electrotechnical Commission (IEC) provides standards for electrical and electronic technology. IEC 31010 describes techniques for identifying risks and how they can be used to make decisions for risk management [5]. NIOSH researchers used guidance provided in this standard to determine FMEA as a suitable technique for identifying EMI-related risk among general device categories. IEC 31010 specifies categories of indicative characteristics to guide in the selection of techniques it describes. FMEA is described as a technique used to identify risks at the department or project level or within equipment or process applications. The FMEA technique is also described as having a diversity of analytical options spanning qualitative, quantitative, and semi-quantitative methods along with a flexible level of effort to suit any applicable timeframe. FMEA requires a moderate level of specialist expertise for making tactical and operational decisions. Stamatis provides that one key benefit of FMEA is that it can be used to establish a system of priority based on failure effects [6]. These characteristics qualify FMEA as a suitable technique for evaluating risk and assigning priority for testing and developing mitigation strategies among categories identified as potentially susceptible to EMI. In this study, FMEA was adopted for determining risk and criticality of potential failure modes among general device categories. The results derived from the FMEA will be used to assign priority for emissions and compatibility testing, developing mitigation strategies, and, in conjunction with EMC standards, promoting electromagnetically safe environments across the mining industry.

METHODOLOGY

For conducting the adopted process of FMEA, NIOSH researchers utilized approval listings of mining products maintained by the Mine Safety and Health Administration (MSHA) Approval and Certification Center (A&CC) [7]. From these lists, 16 general device categories were identified and defined to encompass electronic- and electrical-based devices, components, and safety systems used in underground mining (Table 1). These categories encompass devices that are commonly used in underground coal mining and required to meet safety regulations. An exception is acknowledged for electronic detonator/blasting systems regarding the declined and limited use of permissible explosives in modern underground coal mining operations [8,9,10].

The EMI-related FMEA process adopted by the researchers consists of defining scales for ranking the severity of effects and likelihood of occurrence and detection. Using the adopted scales, ratings for severity, occurrence, and detection were assigned to identified modes of failure associated within each of the 16 device categories. The assigned ratings were then used to calculate a criticality index (CI) and risk priority number (RPN) for each mode of failure.

Table 1. EMI/EMC General Device Categories and Functions.

Device Category	Function
Atmospheric Monitoring Systems	Stationary devices equipped with sensors for monitoring oxygen, toxic and combustible gas, and volatile organic compounds in underground locations
Cap Lamps	General-purpose hardhat-mounted source of light for use in underground mines
Communications/Tracking Systems	Portable handheld/belt worn/stationary nodes that provide for transmitting/receiving intended radio communication signals
Diesel-powered Mine Equipment	Equipment driven by a diesel-powered compression-ignition engine
Electrical Power Systems/Components	Underground mine load centers/power centers that transform voltage and provide control/protection
Electric-powered Mine Equipment	Motor driven equipment powered by battery or underground mine load centers/power centers
Electronic Detonator/Blasting Systems	Device used for detonating explosives
Flashlights	General-purpose handheld source of light for use in underground mines
Handheld Gas Meters	Handheld or belt-worn device equipped with sensors for monitoring oxygen, toxic and combustible gas, and volatile organic compounds
Lighting Systems	Machine-mounted and stationary sources of light used in underground mines
Methane Monitoring Systems	Machine-mounted gas sensor for monitoring for combustible concentrations of methane gas; provides a warning when concentrations of methane reach 1%; shutdown when methane reaches 2%
Personal Sampling Devices	Belt-worn pump for measuring the concentration of airborne contaminants (dusts, fibers, gases, and vapors) for reducing miners' exposure and preventing chronic respiratory diseases
Proximity Detection Systems	Belt-worn component/machine-mounted system used to send a warning signal to the machine operator or stop machine motion when it detects a miner-wearable component within respective zones
Remote Control Transmitters	Handheld device used to wirelessly control machinery from a remote or safe distance from the equipment
Safety Light Devices	Person-worn flashing indicator for ensuring the user is more visible
SCSR Electronics	Provide breathable air for self-escape or refuge during a mine emergency

FMEA requires that ranks for categories of severity, occurrence, and detection be assigned to respective failure modes. These ranks are used in conjunction with calculated indices to evaluate risk associated with particular failure modes and to determine their relative level of significance. This requires the adoption of application-specific definitions and rating scales for each of these three categories. For our research needs, definitions were derived from guidance and standards published and referenced by the American Society for Quality (ASQ) and Society of Automotive Engineers (SAE) [5,11,12]. For the purposes of conducting our FMEA, severity indicates the highest level of consequence resulting from effects potentially experienced during a failure event, with the most severe ranked highest. Occurrence is the likelihood of a failure mode to take place, accounting for available controls to prevent such failures. The most likely of failure modes are ranked highest. Detection is the likelihood for current control(s) to discern the cause, in our case EMI, or the subsequent failure mode. Detection ranks are inverse of those for severity and occurrence, having the least detectable rated highest.

There are many different tables available for ranking severity, occurrence, and detection. Stamatis suggests that ranking tables can be changed to suit application-specific needs and that existing tables can be used as a guideline [5]. For the purposes described here, researchers decided to develop custom tables, through consensus, for rating severity, occurrence, and detection. Here again, these rating schemes were based on guidance and tables afforded by the ASQ and SAE [5,11,12]. For severity of failure, ranks range from 1-10 with the most severe effects ranked as 10 and the least severe as 1. Table 2 describes the associated effects for rating the highest potential severity for a given failure mode. Here, the top two severity ranks concern failure modes that may be hazardous to people with the potential to result in serious or fatal injury. The top ranks are separated by functional failure either having some form of indication, rank 9, or a complete lack thereof, rank 10. Next in order are effects described as a complete loss of function in the absence of being potentially hazardous, including rank 7 with indication of failure and rank 8 without. Following this are failures resulting in a reduced level of operational performance. Included are those affecting the primary function of a device both with and without indication, respectively ranked as 5 and 6; effects limited to a secondary function with and without indication are ranked 3 and 4, respectively. Last in order are severity effects classified as nonperformance issues, ranked as 2 if there is a related concern or 1 if there is no such concern.

Table 2. Rating Criteria for Severity of Failure.

Severity (S)		Effects of Failure Mode	Rank
Catastrophic	Hazardous to People	Hazardous to people without indication: - Affects safe operation -Creates unintended hazards to people - Indication of functional failure IS NOT present - Involves noncompliance with regulation	10
		Hazardous to people with indication: - Affects safe operation -Creates unintended hazards to people - Indication of functional failure IS present - Involves noncompliance with regulation	9
Major	Complete Loss of Function	Loss of function without indication: - Product inoperable - Poses no immediate threat - Indication of functional failure IS NOT present - May involve noncompliance with regulation - May involve equipment damage	8
		Loss of function with indication: - Product inoperable - Poses no immediate threat - Indication of functional failure IS present - May involve noncompliance with regulation - May involve equipment damage	7
	Reduced Performance	Major reduction in performance of primary function without indication: - Primary function operates at a reduced level of performance - Indication of functional failure IS NOT present - May involve noncompliance with regulation	6
		Major reduction in performance of primary function with indication: - Primary function operates at a reduced level of performance - Indication of functional failure IS present - May involve noncompliance with regulation	5
Minor		Minor reduction in performance of secondary function without indication: -Secondary function operates at a reduced level of performance - Indication of functional failure IS NOT present - May involve noncompliance with regulation	4
		Minor reduction in performance of secondary function with indication: - Secondary function operates at a reduced level of performance - Indication of functional failure IS present - May involve noncompliance with regulation	3
	Non-performance Related Issue	Nonperformance related concern: - Overall product performance is unaffected - Noticeable effect that may require further investigation	2
		Not a concern: -Product performance is unaffected -No noticeable effect	1

For ranking occurrence of failures, the researchers needed to employ a qualitative scale due to the limited availability of data for EMI-related events in underground coal mines. A qualitative rating scale is necessary in our case, since failure rate data are insufficient to form quantitative metrics. Occurrence ranks also range from 1-10, with the most likely failure modes ranked as 10 and the least likely as 1. Table 3 provides rating criteria for the likelihood of failure occurrence.

Failure modes most likely to happen are rated highest. The top four ranks are for failure modes having some form of evidence as to their occurrence. Those with a “certain” likelihood are ranked 10 and have some form of supporting documentation. This rank is followed by reported failure modes successfully replicated by NIOSH researchers, using either a source device typically encountered in underground coal operations, rank 9, or an atypical source (i.e. nonapproved device) of electromagnetic energy, rank 8. Rank 7 occurrence is for replicated failures with no known reports; anecdotal information may support these. Ranks 4-6 are for failure modes where EMI is suspected, due to a device having design features that may lead to a failure of similar known occurrence. For this, rank 4 corresponds with similar device failure modes among “moderately high,” rank 7, or “high,” rank 8, occurrences; rank 5 corresponds with similar failure modes of “very high,” rank 9, occurrences; rank 6 is for “certain,” rank 10 occurrences. Rank 3 is assigned to failure modes where occurrence of EMI and device EMC is relatively unknown. In the case where failures are unlikely, rank 2 is given for a device designed for EMC but lacking sufficient testing, while rank 1 is for devices having been validated for EMC.

Table 3. Rating Criteria for Occurrence of Failure.

Occurrence (O)		Likelihood of Failure Mode	Rank
Known	Evidence of EMI	Certain: Likelihood of failure is almost certain - Reported/observed occurrence of failure mode at mining operation - Investigative research conducted by NIOSH and/or stakeholder documentation - HAS supporting documentation - MSHA guidelines and recommendations highlight issue	10
Known	Evidence of EMI	Very high: Likelihood of failure is very high - Reported occurrence of failure mode at mining operation - Replicated failure mode by NIOSH using a typical source under controlled conditions - HAS anecdotal information and some supporting documentation	9
Known	Evidence of EMI	High: Likelihood of failure is high - Reported occurrence of failure mode at mining operation - Replicated failure mode by NIOSH using an atypical source under controlled conditions - HAS anecdotal information and some supporting documentation	8
Known	Evidence of EMI	Moderately high: Likelihood of failure is moderately high - Replicated failure mode - May have anecdotal information and/or some supporting efforts	7
Suspected	Suspicion of EMI	Medium: Medium number of failures likely - Similar design features with device/system having a "certain" likelihood of failure - No anecdotal information nor supporting documentation identified	6
Suspected	Suspicion of EMI	Low: Occasional number of failures likely -Similar design features with device/system having a "very high" likelihood of failure - No anecdotal information nor supporting documentation identified	5
Suspected	Suspicion of EMI	Slight: Few failures likely -Similar design features with device/system having a "moderately high" or "high" likelihood of failure - No anecdotal information nor supporting documentation identified	4
Remote	Unknown EMI/EMC	Very slight: Very few failures likely -Not designed to prevent occurrence of failure mode -No known history of failures and no similar designs	3
Remote	Suspected EMC	Remote: Failures unlikely -Designed specifically to prevent occurrence of failure mode; untested -No known history of failures and no similar designs	2
Remote	Confirmed EMC	Almost never: Failure unlikely -Designed specifically to prevent occurrence of failure mode with respect to EMI; validated -History shows no failures	1

Table 4 includes rating criteria for the detectability of EMI or occurrence of subsequent failure modes. Within this table, detection is classified as either achieved by human observation, ranks 7-10, or incorporated into the device design as a control feature, ranks 2,4,6. At the lowest level of detection, where no indication for functional failure is present, a rank of 10 is assigned. When some form or indication is present but may not be noticeable, a rank of 9 is used. When indications can typically be noticed, rank 8 is used for intermittent changes and rank 7 for sustained changes. Three rankings are used to span the range of detection afforded by devices that employ control features for detection of EMI or a subsequent failure mode. For device controls with undocumented testing, a rank of 6 is used. When a valid test supports relevant detection capability, rank 4 is assigned and rank 2 if such testing is validated.

Using the defined ratings for severity, occurrence, and detection described in Tables 2-4, a five-member panel of NIOSH researchers completed individual ratings for each of sixty-nine modes of failure identified among the 16 associated device categories. Subsequent meetings were held between the researchers to agree upon consensus ranks for severity (S), occurrence (O), and detection (D). From these, indices for criticality index (CI) and risk prioritization number (RPN) were calculated by use of the following formulae.

$$CI = S \times O$$

$$RPN = S \times O \times D$$

Table 4. Rating Criteria for Detection of Failure.

Detection (D)		Detectability of Failure Mode	Rank
Uncertain	Human Detection Controls	Almost impossible: - Failure can typically be detected only after encountering inoperable device - Indication of functional failure IS NOT present	10
Uncertain	Human Detection Controls	Highly uncertain: - Interference may not be noticeable while it is happening - Indication of functional failure IS present	9
Uncertain	Human Detection Controls	Somewhat remote: - Interference may typically be detected due to intermittent change which causes a noticeable change in system performance - Indication of functional failure IS present	8
Uncertain	Human Detection Controls	Low: - Interference may typically be detected due to a sustained change which causes a prolonged change in system performance - Indication of functional failure IS present	7
Uncertain	Device/System Detection Controls	Somewhat certain: - Designed specifically to detect failure mode with no documented testing - Device employs detection features - Device employs audible/visual interference indicators	6
Likely	Device/System Detection Controls	Highly certain: - Designed specifically to detect failure mode and tested - Device employs detection features - Device employs audible/visual interference indicators	4
Likely	Device/System Detection Controls	Certain: - Designed specifically to detect failure mode, tested, and validated - Device employs detection features - Device employs audible/visual interference indicators	2

As previously mentioned, qualitative ratings were subjectively determined through the consensus of research team members. Thereby, in this case, CI and RPN are also, by result, subjective determinations. Despite being subjective in nature, qualitative techniques are justified since they afford a means for obtaining conclusive results [13].

Typical methods of conducting risk assessment with FMEA use severity (S), CI, and RPN, in order of successive priority, to set risk-based prioritization among modes of failure [5]. More recently, the Automotive Industry Action Group (AIAG) and German Association of the Automotive Industry (VDA) recommend using action priority (AP) [14]. By using an AP table, actions can be prioritized based on combinations of S, O, and D rankings, providing advantage over the use of single metrics or derivations thereof [14,15]. NIOSH researchers selected to use the AP approach for assigning priority to EMI equipment and device evaluations. Using this approach allows the focus to be placed on actions for reducing risks associated with EMI. For this, the researchers’ decided to raise the level of priority given to known failures of major severity and uncertain detection. This was intended to focus assessments on device categories having a greater opportunity to result in risk reducing action. Whereas without AP, assessments given priority based on a severity first approach, such as those of catastrophic severity and remote occurrence, may result in an underutilization of resources by testing electromagnetically compatible devices. The AP classifications developed to suit our EMI research needs are summarized in Table 5.

Table 5. Action Priority Classifications

Action Priority (AP)	Criteria
High	Catastrophic Severity with Known or Suspected Occurrence when Detection is Uncertain
	Major Severity with Known Occurrence when Detection is Uncertain
Medium	Catastrophic Severity with Known or Suspected Occurrence when Detection is Likely
	Catastrophic Severity with Remote Occurrence when Detection is Uncertain
	Major Severity with Known Occurrence when Detection is Likely
	Major Severity with Suspected Occurrence when Detection is Uncertain
Low	Catastrophic Severity with Remote Occurrence when Detection is Likely
	Major Severity with Suspected Occurrence when Detection is Likely
	Major Severity with Remote Occurrence
	Minor Severity

For our AP, the "High" rank device categories are intended to receive priority. These include failures with catastrophic effects where occurrence is either known or suspected and their detection is uncertain, as well as failures having major effects of known occurrence and uncertain detection. Next in line are "Medium" AP ranked failure modes, being either catastrophic or major in severity. Catastrophic severities within this rank are of known or suspected occurrence when detection is likely or of remote occurrence when detection is uncertain; major severities here are of known occurrence when detection is likely or of suspected occurrence when detection is uncertain. Lastly are the "Low" AP ranked failures. This rank includes all minor severities along with those remaining of catastrophic and major severity.

The researchers defined ranges of S, O, and D for AP classification using a consensus-based approach. Here, failure effects are divided into three categories, classified in order of increasing severity as "Minor," "Major," and "Catastrophic." Each is defined by an S rank having a range of 1-4, 5-8, and 9-10, respectively. There are three classes for failure occurrence, listed in order of increasing likelihood as "Remote," "Suspected," and "Known." These are defined using the O rank with a range of 1-3, 4-6, and 7-10, respectively. For detection of failure, two classes are used as either "Likely," with D ranks of 2 and 4, or "Uncertain," with a D rank range of 6-10. These ranges defined in terms of S, O, and D rankings are respectively included in Tables 2-4, and referenced in Table 6 for AP classification. For determining EMI assessment priority, the sixty-nine modes of failure considered in this study are sorted in terms of priority by using, in order of precedence, AP, S rank, CI, and RPN.

Table 6. AP classification in terms of S, O, and D ranges.

Severity (S)	Occurrence (O)	Detection (D)	Action Priority (AP)
Catastrophic (9-10)	Known (7-10)	Uncertain (6-10)	High
		Likely (2,4)	Medium
	Suspected (4-6)	Uncertain (6-10)	High
		Likely (2,4)	Medium
	Remote (1-3)	Uncertain (6-10)	Medium
		Likely (2,4)	Low
Major (5-8)	Known (7-10)	Uncertain (6-10)	High
		Likely (2,4)	Medium
	Suspected (4-6)	Uncertain (6-10)	Medium
		Likely (2,4)	Low
	Remote (1-3)	Uncertain (6-10)	Low
		Likely (2,4)	Low
Minor (1-4)	Known (7-10)	Uncertain (6-10)	Low
		Likely (2,4)	Low
	Suspected (4-6)	Uncertain (6-10)	Low
		Likely (2,4)	Low
	Remote (1-3)	Uncertain (6-10)	Low
		Likely (2,4)	Low

RESULTS AND DISCUSSION

FMEA

For the FMEA, researchers assigned individual S, O, and D rankings for each of the sixty-nine modes of failure considered in this study. Twenty-four of these modes are classified as catastrophic (S of 9-10), having the potential to result in serious or fatal injury, summarized in Table 7. These are typically the most significant in terms of risk and should be given careful consideration in terms of assessment priority. All are within the top 20 priorities for our EMI assessment. Of these, three device categories have failure modes rated in the range of known occurrence (O of 7-10). They include proximity detection systems (PDSs), remote control transmitters, and handheld gas meters. For these, the following information was considered in part of rating their likelihood for occurrence. PDS interference is addressed through regulatory and manufacturer safety notices. In 2016, MSHA published a notice advising underground mine operators that PDS performance can be affected by electrical devices/equipment placed in close proximity to the miner-wearable component, and that operators should investigate such sources for preventing EMI [16]. Regarding remote control transmitters, MSHA issued Program Information Bulletins (PIB) regarding the use of magnets near remote-control operated equipment transmitters [17]. Magnets are deemed an atypical source here. Handheld gas meters have been reported as suspected victims of EMI. This information was revealed through discussions with the MSHA A&CC. NIOSH researchers conducted preliminary tests to investigate associated modes of failure. They successfully replicated reported failure effects and further observed that instrument shutdown is possible when subjected to an atypical source of electromagnetic energy (e.g. 25-watt mobile radio).

Table 7. Top-ranking "Catastrophic" Severity Results

Device Category	Failure Mode	AP	S	O	D	CI	RPN	Priority
Proximity Detection Systems	Failed equipment shutdown	H	10	10	10	100	1000	1
	Failed warning							
	Communication interference							
	Inoperable	H	10	8	10	80	800	2
	Shutdown	M	9	3	6	27	162	19
Remote Control Transmitters	Unintended equipment operation	H	10	8	10	80	800	2
	Failed equipment operation	H	9	6	7	54	378	5
Atmospheric Monitoring Systems	Failed alarm	H	10	5	10	50	500	3
	False reading							
	Shutdown	H	9	4	9	36	324	6
	Inoperable	M	9	3	9	27	243	17
Handheld Gas Meters	Failed alarm	H	10	5	10	50	500	3
	Shutdown	H	9	8	9	72	648	4
Methane Monitoring Systems	Failed equipment shutdown	H	10	5	10	50	500	3
	Failed warning							
	False reading							
	Inoperable	M	9	3	8	27	216	18
Diesel-powered Mine Equipment	Unintended operation	M	10	3	10	30	300	15
Electrical Power Systems/Components	Failed trip	M	10	3	10	30	300	15
Electric-powered Mine Equipment	Unintended operation	M	10	3	10	30	300	15
Electronic Detonator/Blasting Systems	Inoperable	M	10	2	10	20	200	16
	Unintended ignition							
	Failed ignition	M	9	2	9	18	162	20
Communications/Tracking Systems	Shutdown	M	9	3	9	27	243	17

The research team ranked some of the failure modes associated with atmospheric monitoring systems (AMSs) and methane monitoring systems as catastrophic suspected occurrence (O of 4-6). Occurrence is suspected for these due to their having similar failure modes ranked as known occurrence or by their having similar design features as handheld gas meters, where corresponding failures are known to occur. The remaining catastrophic failure modes associated with device categories including diesel- and electric-powered mine equipment, electrical power systems/components, electronic detonator/blasting systems, and communications/tracking systems all have remote ranked likelihoods for occurrence (O of 1-3).

EMI Assessment Priority

To determine priority for EMI assessments, the various device categories and their respective modes of failure were sorted first according to each of the three AP classes ("High," "Medium," "Low"), followed respectively by their S rank (10-1), CI (100-1), and RPN (1000-1). The top five device categories ranked within the "High" AP class, in order of their highest priority failure mode are: 1) PDSs, 2) remote control transmitters, 3) atmospheric monitoring systems/handheld gas meters/methane monitoring systems, 4) cap lamps/personal sampling devices, and 5) communications/tracking systems. "High" AP results are presented in Table 8 with associated mode(s) of failure, FMEA ratings, and their respective assessment priority.

Table 8. Top-ranking "High" Action Priority Results.

Device Category	Failure Mode	AP	S	O	D	CI	RPN	Priority
Proximity Detection Systems	Failed equipment shutdown		10	10	10	100	1000	1
	Failed warning							
	Communication interference							
	Inoperable		10	8	10	80	800	2
	False equipment shutdown		5	10	9	50	450	11
	False warning		5	10	7	50	350	12
Remote Control Transmitters	Unintended equipment operation		10	8	10	80	800	2
	Failed equipment operation		9	6	7	54	378	5
Atmospheric Monitoring Systems	Failed alarm		10	5	10	50	500	3
	False reading							
	Shutdown		9	4	9	36	324	6
	False alarm	H	5	9	8	45	360	13
Handheld Gas Meters	Failed alarm		10	5	10	50	500	3
	Shutdown		9	8	9	72	648	4
	False alarm		6	9	10	54	540	9
	False reading							
Methane Monitoring Systems	Failed equipment shutdown		10	5	10	50	500	3
	Failed warning							
	False reading							
Cap Lamps	Inoperable		7	8	9	56	504	7
	Shutdown		7	8	7	56	392	8
Personal Sampling Devices	Shutdown		7	8	9	56	504	7
	Overflow		6	8	10	48	480	10
	Underflow							
	Flow fault		5	8	6	40	240	14
Communications/Tracking Systems	Communication interference		5	10	9	50	450	11

Results show that three modes of failure among device category 1 (proximity detection systems, PDSs) are priority 1. They include failed equipment shutdown, failed warning, and communication interference. These modes are potentially catastrophic with known occurrence and uncertain detection. Overall, they have the highest possible rankings for S, O, and D and by result, CI, and RPN as well. Tied for priority 2 are category 1 (PDSs) – inoperable and category 2 (remote control transmitters) – unintended equipment operation. These modes of failure are also considered to be potentially catastrophic with known occurrence and uncertain detection. However, they are slightly lower in terms of priority from having a slightly lower O rank of 8. There are various device categories and failure modes associated as priority 3. These encompass category 3 (atmospheric monitoring systems, AMSs) – failed alarm/false reading, category 3 (handheld gas meters) – failed alarm, and category 3 (methane monitoring systems) – failed equipment shutdown/failed warning/false reading. For these, severity is still potentially catastrophic and detection uncertain, but with O ranked at 5, having a suspected likelihood of occurrence. For handheld gas meters – shutdown, remote control transmitters – failed equipment operation, and AMSs – shutdown, all have S ranks of 9. These are marked, in respective order, as priorities 4, 5, and 6. The precedent failure mode for category 4 (cap lamps) is inoperable and category 4 (personal sampling devices) is shutdown. These are equal in terms of assessment as priority 7. The remaining modes of failure among the "High" AP class are priorities 8-14. Included among these is category 5 (communications/tracking systems) – communication interference, tied for priority 11 with category 1 (PDSs) – false equipment shutdown.

Some device categories with catastrophic severity rankings were excluded from the "High" AP class due to their "Remote" chance of occurrence. These include diesel- and electric-powered mine equipment, electrical power systems/components, and electronic detonator/blasting systems. Despite having a remote chance of occurrence and therefore lower criticality index, these failure modes are still very important in terms of severity.

The top 10 priority failure modes and associated device categories are summarized in Table 9. A complete list of results afforded by the FMEA with AP is included in the Appendix section. In this study, FMEA is applied to general device categories and their identified modes of failure. Device categories discussed in this paper are based on the victim side of an EMI instance, although some of the devices can be either a victim or a source. In each case, subjective rankings define risk associated with a particular event. Risk is inherent danger, of which metrics should not be tied, with a threshold level of safety. The concept of defining a threshold of minimum risk is a common misconception. FMEA does not accept such a threshold, but only attempts to assess and prioritize associated risk. Therefore, any threshold assigned by the user or reviewer of the FMEA is not rooted in the process, but rather an assumption made by that person. Lower rankings do not exclude an event, including a serious life-threatening event, from occurring or resulting in serious consequences and should not be interpreted as such.

Table 9. Top 10 Priority Failure Modes.

Rank	Device Category	Potential Failure Mode (Priority)
1	Proximity Detection Systems	Failed equipment shutdown (1) Failed warning (1) Communication interference (1) Inoperable (2)
2	Remote Control Transmitters	Unintended equipment operation (2) Failed equipment operation (5)
3	Atmospheric Monitoring Systems	Failed alarm/False reading (3) Shutdown (6)
	Handheld Gas Meters	Failed alarm (3) Shutdown(4) False alarm (9) False reading (9)
	Methane Monitoring Systems	Failed equipment shutdown (3) Failed warning (3) False reading (3)
4	Cap Lamps	Inoperable (7) Shutdown (8)
	Personal Sampling Devices	Shutdown (7) Overflow/Underflow (10)

CONCLUSIONS

Due to the limited availability of information regarding EMI-related events among devices used in underground coal mining, a qualitative approach was used to conduct a FMEA by subjectively rating S, O, and D associated with failure modes caused by EMI events. Despite being subjective in nature, qualitative techniques are justified since they afford a means for obtaining conclusive results through consensus. The process described can be used for a continual assessment of risk associated with EMI in mining. The results of this process can be used to determine where the priority for assessment is most critical and can be adapted to improve controls and mitigation strategies.

The FMEA results used in conjunction with AP show that PDSs present the greatest level of risk among general device categories considered in this study and, therefore, should be the primary focus for EMI/EMC assessments. For PDSs, failed equipment shutdown, failed warning, and communication interference are priority 1 among its own and all other failure modes considered in this study. PDSs are further justified as being the top priority for EMI assessments since its inoperable failure mode is inclusive of priority 2. Although NIOSH has previously investigated PDS susceptibility to EMI, additional research is needed to improve its EMC. Following PDSs in rank are remote control transmitters. Unintended equipment operation caused by remote control transmitter interference follows as priority 2 among all failure modes. This category is also significant in terms of risk and must be a top focus in conducting EMI/EMC evaluations. Priority 3 is a three-way tie between AMSs, handheld gas meters, and methane monitoring systems. The associated failure modes are failed alarm and false reading for AMSs; failed alarm for handheld gas meters; failed equipment shutdown, failed warning, and false reading for methane monitoring systems. These five top-three ranked device categories encompass the top six priority failure modes. This strongly supports the decision to assign these devices priority in conducting emissions and susceptibility testing.

Cap lamps and personal sampling devices include priority 7 and 8 failure modes. These are also salient in terms of risk-reducing action. Catastrophic failure modes associated with device categories ranked outside the "High" AP category are also important to consider. These include diesel- and electric-powered mine equipment, electrical power systems/components, and electronic detonator/blasting systems.

The FMEA process conducted in part of this research was used to assign priority among 16 categories of devices/equipment used in underground coal mining. The top three, ranked in order or priority, are: 1) PDSs, 2) remote control transmitters, and 3) AMSs, handheld gas meters, and methane monitoring systems. Focus should be directed to these device categories in terms of their EMI assessment priority.

LIMITATIONS

The FMEA presented in this paper represents general categories of devices used in underground mining. The scope of this baseline analysis is to determine priority for individual device assessments. Resources used to conduct the FMEA are limited to the experience of the five-member team of NIOSH researchers that participated in the analysis and availability of information collected in cooperation with the MSHA A&CC. This study is further limited by the lack of quantitative data for EMI-related events in underground coal mines. Individual devices must be thoroughly evaluated using a comprehensive assessment plan in order to accurately determine their EMC and any EMI-related risk associated with their use in underground coal mining. The list of device categories presented here may not be all inclusive, and assessment priority may change upon discovery of new information and/or implementation of improved control measures.

DISCLAIMER

While the FMEA results can be used to assess risk, it is ultimately each mine's unique characteristics and situations that drive associated risk. The process discussed in this paper can be applied to risk factors that are identified for a specific application, in this case setting priority for EMI assessments. Changing the application will affect the defined scales for S, O, and D applied in the FMEA and ultimately the assigned rankings and corresponding results.

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

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APPENDIX

Rank	Device Category	Failure Mode	AP	S	O	D	CI	RPN	Priority
1	Proximity Detection Systems	Failed equipment shutdown	H	10	10	10	100	1000	1
		Failed warning	H	10	10	10	100	1000	1
		Communication interference	H	10	10	10	100	1000	1
		Inoperable	H	10	8	10	80	800	2
		False equipment shutdown	H	5	10	9	50	450	11
		False warning	H	5	10	7	50	350	12
		Shutdown	M	9	3	6	27	162	19
2	Remote Control Transmitters	Unintended equipment operation	H	10	8	10	80	800	2
		Failed equipment operation	H	9	6	7	54	378	5
		Inoperable	M	7	6	9	42	378	21
		Shutdown	L	7	3	9	21	189	26
3	Atmospheric Monitoring Systems	Failed alarm	H	10	5	10	50	500	3
		False reading	H	10	5	10	50	500	3
		Shutdown	H	9	4	9	36	324	6
		False alarm	H	5	9	8	45	360	13
		Inoperable	M	9	3	9	27	243	17
	Handheld Gas Meters	Failed alarm	H	10	5	10	50	500	3
		Shutdown	H	9	8	9	72	648	4
		False alarm	H	6	9	10	54	540	9
		False reading	H	6	9	10	54	540	9
		Inoperable	L	7	3	9	21	189	26
	Methane Monitoring Systems	Failed equipment shutdown	H	10	5	10	50	500	3
		Failed warning	H	10	5	10	50	500	3
		False reading	H	10	5	10	50	500	3
		Inoperable	M	9	3	8	27	216	18
		Shutdown	M	7	4	8	28	224	23
		False equipment shutdown	M	6	5	10	30	300	24
		False warning	M	6	5	10	30	300	24
4	Cap Lamps	Inoperable	H	7	8	9	56	504	7
		Shutdown	H	7	8	7	56	392	8
		Flicker, brighten/dim	L	3	9	8	27	216	30
		Unintended activation	L	3	8	7	24	168	31
	Personal Sampling Devices	Shutdown	H	7	8	9	56	504	7
		Overflow	H	6	8	10	48	480	10
		Underflow	H	6	8	10	48	480	10
		Flow fault	H	5	8	6	40	240	14
		Inoperable	L	7	3	9	21	189	26
5	Communications/Tracking Systems	Communication interference	H	5	10	9	50	450	11
		Shutdown	M	9	3	9	27	243	17
		Inoperable	M	7	6	9	42	378	21
		Unintended communication	L	6	3	10	18	180	28
6	Diesel-powered Mine Equipment	Unintended operation	M	10	3	10	30	300	15
		Inoperable	L	7	3	9	21	189	26
		Failed operation	L	5	3	8	15	120	29
	Electrical Power Systems/Components	Failed trip	M	10	3	10	30	300	15
		Inoperable	L	7	2	9	14	126	27
		False trip	L	5	3	8	15	120	29
	Electric-powered Mine Equipment	Unintended operation	M	10	3	10	30	300	15
		Inoperable	L	7	3	9	21	189	26
		Failed operation	L	5	3	8	15	120	29
7	Electronic Detonator/Blasting Systems	Inoperable	M	10	2	10	20	200	16
		Unintended ignition	M	10	2	10	20	200	16
		Failed ignition	M	9	2	9	18	162	20
8	Flashlights	Inoperable	M	7	4	9	28	252	22
		Shutdown	M	5	4	7	20	140	25
		Flicker, brighten/dim	L	3	5	8	15	120	35
		Unintended activation	L	3	3	7	9	63	36
	Lighting Systems	Inoperable	M	7	4	9	28	252	22
		Shutdown	M	5	4	7	20	140	25
		Flicker, brighten/dim	L	3	5	8	15	120	35
		Unintended activation	L	3	3	7	9	63	36
	Safety Light Devices	Inoperable	M	7	4	9	28	252	22
		Shutdown	M	5	4	7	20	140	25
		Flicker, brighten/dim	L	3	5	8	15	120	35
		Unintended activation	L	3	3	7	9	63	36
9	SCSR electronics	Inoperable	L	3	6	9	18	162	32
		Communication interference	L	3	6	8	18	144	33
		Shutdown	L	3	5	9	15	135	34
		False detection	L	3	5	8	15	120	35