WEST VIRGINIA BOARD OF COAL MINE HEALTH AND SAFETY

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15 December 2011

To: Chairman of the Joint Committee on Government and Finance

From: Joel L. Watts
Health and Safety Administrator
West Virginia Board of Coal Mine Health and Safety

Re: HB2437

Mr. Chairman,

During the 2011 Session of the West Virginia Legislature, the Board of Coal Mine Health and Safety (Coal Board) was charged with the following:

> The Board of Coal Mine Health and Safety is directed to conduct a study of the safety of installation of methane detection shut-off devices on machine extraction apparatus, including, but not limited to, long wall sheers and cutter heads. The Office shall study the benefits and appropriateness of requiring the installation of these devices, to determine if there are safety benefits, and whether the Office recommends to the Legislature that requirements regarding mandating these devises in underground mines is warranted. The Office shall report to the Legislature's Joint Committee on Government and Finance by December 31, 2011 with recommendations regarding whether it is appropriate to implement any requirements.

This report is in fulfillment of that obligation. The Board would like to recommend to the Legislature the following:

- The Board anticipates at the January 2012 meeting, which will take place on the 10th and 11th, that a vote will be taken to send out for the 30-day required comment period an amendment to 36.14. We further anticipate that a final promulgation will take place during the February meeting.

Attached to this recommendation is the rule expected to be proposed as well as a report drafted under the supervision of Dr. Chris Bise, Coal and Energy Research Bureau at West Virginia University.

TITLE 36 SERIES 14

ELECTRICAL EQUIPMENT IN MINES; REQUIRED EXAMINATIONS

§36-14-1. General.

1.1 Scope. Rules and regulations governing electrical equipment in mines; required examinations.

1.2 Authority. W. Va. Code 22-6-4

1.3 Filing Date. ________________

1.4 Effective Date. _____________

§36-14-2. Effect of Regulations.

2.1. These rules and regulations shall have the effect of law and violations shall be deemed a violation of law and so cited with the same effect as law. All provisions of Article 1A, Chapter 22A of the Code relative to the enforcement of these rules and regulations.

§36-14-3. Definitions.

All terms in these rules and regulations, not defined herein, shall have the meaning set forth in Section 1, Article 1A, Chapter 22A of the Code.

§36-14-4. Electric Equipment in Mines.

(a) All examinations, as required in ~~the~~ paragraphs A through G below, shall be made at a point not less than twelve (12) inches from the roof, face and ribs using an approved handheld detector.

(b) In all mines, electric haulage locomotives operated from trolley wire and all other non-permissible electrical equipment or devices which may ignite gas shall not be used in return air, unless permission is granted by Director of the Department of Mines for a specified area. Permissible electrical equipment may be used in return airways: Provided, That (a) The mine operator gives notice to the Inspector-at-Large or the District Mine Inspector in the division in which the mine is located, when such work is performed in return airways at any point exceeding four hundred (400) feet out by the last open crosscut; (b) the work area is preshift examined in accordance with Chapter 22A, Article 2, Section 20 of West Virginia code; (c) the mine foreman or assistant mine foreman examines the working area in the return airway in which miners will be working at the beginning of each shift before any equipment is energized; (d) the working area is examined at least every two (2) hours during a working shift for hazards, by a certified mine foreman or assistant mine foreman; (e) methane gas examinations are made at frequent intervals as work progresses, but not to exceed twenty (20) minutes; (f) the electrical equipment is examined at least once each shift for permissible deficiencies, (g) no temporary splices are in the trailing cables of the equipment being used, and (h) the work area is provided with two portable fire extinguishers. For the purpose of this provision, return air shall mean a volume of air that has passed through and ventilated all the working place in a mine section.

(c) No person shall be placed in charge of a coal-cutting machine in any mine who is not a qualified person, capable of determining the safety of the roof and sides of the working places and of detecting the presence of explosive gas, unless they are accompanied by a certified or qualified person who has passed such examination.

(d) In any mine no machine shall be brought inby the last breakthrough next to the working face until the machine man shall have made an inspection for gas in the place where the machine is to work. If explosive gas in excess of one (1%) percent is found in the place, the machine shall not be taken in until the danger is removed.

(e) In working places a ~~safety lamp, or other~~ suitable approved ~~apparatus~~ detector for the detection of explosive gas, shall be provided for use with each mining machine when working, and should any indication of explosive gas in excess of one (1%) percent appear on the ~~flame of the safety lamp, or on other apparatus~~ detector used for the detection of explosive gas, the person in charge shall immediately stop the machine, cut off the current at the nearest switch and report the condition to the mine foreman or supervisor. The machine shall not again be started in such place until the condition found has been corrected and been pronounced safe by a certified person.

(f) No electric equipment shall be operated in a mine for a longer period than twenty (20) minutes without an examination as above described being made for gas; and if gas is found in excess of one (1%) percent, the current shall at once be switched off the machine, and the trailing cable shall forthwith be disconnected from the power supply until the place is pronounced safe by a certified person.

(g) Machine runners and helpers shall use care while operating mining machines. No person except those persons necessary shall remain near the machine while it is in operation. They shall examine the roof of the working place to see that it is safe before starting to operate the machine. They shall not move the machine while the cutter chain is in motion.

§36-14-5. Methane Monitors

5.1(1) MSHA approved methane monitors shall be installed on all face cutting machines, continuous miners, longwall face equipment, loading machines, and other mechanized equipment used to extract or load coal within the working place.

(2) The sensing devices of methane monitors shall be installed as close to the working face as practicable.

(3) Methane monitors shall be maintained in permissible and proper operating condition and shall be calibrated with a known air-methane mixture at least once every 15 days. To assure that methane monitors are properly maintained and calibrated, the operator shall:

(i) Use persons properly trained in the maintenance, calibration, and permissibility of methane monitors to calibrate and maintain the devices.

(ii) Maintain a record of all calibration tests of methane monitors. Records shall be maintained in a secure book that is not susceptible to alteration or electronically in a computer system so as to be secure and not susceptible to alteration.

(iii) Retain the record of calibration tests for 1 year from the date of the test. Records shall be retained at a surface location at the mine and made available for inspection by authorized representatives of the Director and the representative of miners.

5.2(1) When the methane concentration at any methane monitor reaches 1.0 percent the monitor shall give a warning signal.

(2) The warning signal device of the methane monitor shall be visible to a person who can deenergize electric equipment or shut down diesel-powered equipment on which the monitor is mounted.

5.3 When the methane concentration at any methane monitor reaches 1.25 percent the cutting mechanism for such equipment will be automatically deenergized.

5.4 The methane monitor shall automatically deenergize electric equipment or shut down diesel-powered equipment on which it is mounted when--

(1) The methane concentration at any methane monitor reaches 2.0 percent; or

(2) The monitor is not operating properly.

§36-14-~~5~~ 6. Cutting and Welding in Mines.

~~5~~ 6.1 When cutting and welding has been performed in any area of an underground coal mine, that area shall be examined for any hot spots immediately after the work is completed. A second examination for hot spots shall be conducted within 2 hours, but no sooner than 30 minutes after the first examination has been completed. The second examination shall be performed by a qualified person and recorded in a book provided for that purpose by a certified person.

Review of Methane Monitoring and Automatic Shut-Down Regulations and Standards for Electrically Powered Underground Coal Mine Face Equipment

Prepared for the
West Virginia Board of Coal Mine Health & Safety

November 14, 2011

Revision 1—December 8, 2011

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Executive Summary

Pursuant to the requirements of House Bill 2437, the West Virginia Board of Coal Mine Health & Safety requested an investigation into methane monitoring systems on electrically powered face equipment and the threshold level at which an automatic equipment de-energization is initiated.

This review considers a scientific rationale underlying the Federal (MSHA) regulations requiring de-energization of equipment at a methane concentration level of one percent and automatic shut-down at a methane concentration of two percent. This rationale is common throughout hydrocarbon processing industries and is applicable to the conditions of underground bituminous coal mining.

The existing West Virginia regulations are compared to other states and regulatory agencies. Only the Commonwealth of Pennsylvania has an automatic de-energization regulation, which is similar to the Federal regulations that are the default for the remaining states.

The causes of methane ignitions are summarized, and data demonstrates that frictional ignition sources, not electrical arcs, are the root causes of most methane ignitions at the face. The special case of roof bolters is also reviewed, and frictional ignitions are found, likewise, to be the predominant cause. In all cases where mechanical equipment cuts coal, worn bits and sandstone are positively correlated to ignitions.

Methane monitor performance, necessary for a reliable monitoring scheme, is discussed based on research studies for continuous miners and longwall shearers. Monitor location and response time are both significant design factors. Improvements in methane monitoring indicate that the results of earlier response time research are likely conservative. Catalytic heat of combustion and infrared sensor types are comparable with the largest impediment to acceptable response time for either being attributable to fouled protective caps on the sensors themselves. Location studies are relevant independent of sensor type considered.

The interaction of methane and coal dust is summarized, providing additional justification for the necessity to limit methane ignitions.

These interrelated areas, viewed together, indicate that elimination of frictional ignitions is the critical element to provide for methane safety at the working face. Thus, de-energization and/or disconnection of the power source, whether manually or automatically, has benefit only insofar as this action eventually stops the rotation of the cutter head, thereby removing its ability to create a source of ignition created by the contact of cutting bits with non-coal rock.

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1.0 Background

Pursuant to H. B. 2437, the Legislature of West Virginia amended the Code of West Virginia, 1931, by adding thereto a new section, designated §22A-6-11, quoted as follows:

> Article 6. Board of Coal Mine Health and Safety.
>
> §22A-6-11. Study of methane detecting shut off devices.
>
> Study of Automatic shut-down of mining machines. –The Board of Coal Mine Health and Safety is directed to conduct a study of the safety of installation of methane detection shut-off devices on machine extraction apparatus, including, but not limited to, long wall sheers and cutter heads. The Office shall study the benefits and appropriateness of requiring the installation of these devices, to determine if there are safety benefits, and whether the Office recommends to the Legislature that requirements regarding mandating these devises in underground mines is warranted. The Office shall report to the Legislature's Joint Committee on Government and Finance by December 31, 2011 with recommendations regarding whether it is appropriate to implement any requirements.

The addition of this section, and the introduction of H. B. 2437 were prompted by the concerns of some West Virginia coal miners, who petitioned their elected officials to modify State law. At issue is the orientation that Federal regulations require that equipment be automatically de-energized when methane levels reach two percent, whereas State requirements do not allow for the mining of coal when methane levels exceed one percent. It was suggested that equipment automatically de-energize when methane levels reach one percent.

To achieve the goals of §22A-6-11, the West Virginia Board of Coal Mine Health and Safety requested an investigation into the following questions:

1) The background for the current standards. What is the science behind using either one percent or two percent methane? Is it the right number?
2) What do accident/incident investigations reveal about methane ignitions?
3) How do other states (and, possibly, countries) address the methane concentration issue?
4) Why does methane seem to be more of an issue at a cutter head (CM/shearer) than with a bolter?
5) In consideration of the methane question, what is the interactive effect, quantitatively, between methane and coal dust?
6) What is the effect of the mounting location for the methane detector on the equipment (note that this is not typically in the 12-inch "window" in which manual readings are taken).
7) How many major methane incidents have been caused by ignition at the cutter head versus other ignition sources such as burning and welding?

These questions have been grouped into five categories of objectives, herein called "Aims," and will be addressed in separate, though necessarily interconnected, sections of this report. This format will allow for the inclusion of additional information which, hopefully, adds to clarity of understanding of multiple interacting elements.

Aim 1: To determine the appropriateness of the current regulations for automatic de-energization of electrically powered face equipment at a methane concentration of two percent by volume.

Rationale: Following the Federal Coal Mine Health and Safety Act of 1969, MSHA considered some scientific and/or engineering basis for establishing the current regulations of 30 CFR §75.323 and related sections, requiring that equipment was to be de-energized at one percent methane and power was to be automatically disconnected at two percent methane.

Analysis Plan: Flammable gases are present in many industrial processes where forced ventilation, obstructions to ventilation, sources of ignition, and gas concentration monitoring systems are similar to those conditions encountered in underground bituminous coal mining. The engineering design criteria used in the hydrocarbon and petrochemical processing industries, among others, would have process monitoring and shutdown guidelines similar to those that were incorporated in the MSHA regulations for underground bituminous coal mines.

Aim 2: To compare the West Virginia State Code §22A-2-43, regarding methane at the working face, to regulations of other states and agencies.

Rationale: State, Federal, and other agencies may have enacted, for various reasons, more conservative methane regulations since the Federal regulations of 30 CFR §75 were enacted in 1969.

Analysis Plan: Regulators considering methane levels in underground coal mines for those states with such regulations governing active underground bituminous coal mines would, if deemed necessary, enact more conservative methane standards. These would be considered along with related Federal regulations. Additionally, the National Fire Protection Agency, originators of the National Electric Code on which many of the electrical regulations of 30 CFR §75 are based, will also have applicable standards with which to compare those from the State of West Virginia.

Aim 3: To characterize the hazard associated with the interplay of electrically powered face equipment and methane ignitions.

Rationale: De-energizing electrically powered face equipment in the presence of methane must be valuable because it eliminates (or reduces) the hazard of an ignition of methane at the face. Three components are necessary for an ignition to occur: fuel, oxygen, and a source of heat sufficient to cause the ignition. The fuel (methane) must be assumed to be present since this is the topic of question as to actions to take when the methane monitor registers a concentration of the gas. The oxygen must also be assumed to be present since the working place is ventilated to maintain approximately 20% oxygen for human respiration. The remaining factor would be the presence of a heat source sufficient to cause ignition of a methane-air mixture. The hypothesis becomes that this is avoidable by de-energizing the electrically-powered face equipment.

Analysis Plan: Historical studies for decades of methane ignitions, based on MSHA and U. S. Bureau of Mines data, can provide insight in to the nature of ignition sources. This historical data, once ignition sources are identified, would be followed by a trail of research aimed at eliminating or reducing the likelihood of methane ignitions at the face. An historical review would provide insight into the mechanisms responsible for generating sufficient heat to ignite methane and the approaches taken to address the associated concerns. Such an analysis would consider continuous miners, longwall shearers, and bolters, as well as ignitions caused by events such as burning and welding.

Aim 4: To assess the capabilities of machine-mounted sensors with regard to their ability to detect levels of methane and cause an automatic process shutdown (*i.e.* de-energize power to mining operations).

Rationale: In order for guidelines and/or regulations to be appropriate, the methane sensing system on the equipment must be capable of responding appropriately to the selected shutdown threshold.

Analysis Plan: Studies of response time and monitor location have been undertaken for continuous miners and longwall shearers. Some of these analyses were performed for an earlier generation of methane monitors. While the conclusions for monitor locations would be appropriate for current mining environments, those based on response time would likely represent a more conservative view than one based on more recent instrumentation.

Aim 5: To quantitatively assess the interactive effect of coal dust and methane in the event of an ignition.

Rationale: It has been shown that methane ignitions are capable of dispersing coal dust, leading to more serious, violent explosions.

Analysis Plan: Much research has addressed the interaction of methane ignitions and coal dust explosions. Literature exists that reasonably quantifies this relationship.

These aims are addressed in Sections 2-6.

2.0 Monitoring of Flammable Gases

Aim 1: To determine the appropriateness of the current regulations for automatic de-energization of electrically-powered face equipment at a methane concentration of two percent by volume.

The monitoring of hazardous and flammable gases is not unique to the detection of methane in coal mines. Concerns about fire and explosion are prominent in all industries where such gases are present. Methane is a hydrocarbon and the hydrocarbon and petrochemical processing industries have experience with methane and other flammable gases. Natural gas, for example, is primarily methane (CH_4). Their design criteria are applicable to underground bituminous coal mining.

2.1 Choosing the Threshold Value for the Methane Detector

Frequently, there are questions as to the origin of the threshold value of one percent concentration, by volume, of methane at which it is required for operators to de-energize equipment. How does one arrive at one percent? The one percent value is derived by considering the explosive range of methane in air, which is approximately 5-15%. Typically, the low alarm set-point for flammable gas is assigned to that value which represents 20% of the lower explosive limit (LEL) [or lower flammable limit (LFL)] of the gas. The petrochemical and hydrocarbon processing industries have experience with methane and natural gas, for which methane constitutes the largest component, supplemented by other saturated hydrocarbon gases such as ethane. In choosing alarm set-points, the Center for Chemical Process Safety recommends:

> <u>8.1.3.1. Gas Detection Alarm Levels</u>
> Flammable gas detection systems are typically used to initiate an alarm at a concentration level below the lower flammable limit (LFL). Two gas alarm levels (low and high) are often utilized to allow early warning prior to taking automatic actions. Detection systems may also be used to stop electrical power and initiate process shutdown. The low alarm set point should be ~20% LFL and the high alarm level set point should be between 40%~60% LFL. Where these devices are used to initiate process shutdown or activate fire protection systems, it is common practice to use some form of voting, typically 2 out of 2, such that the frequency of spurious shutdowns or system activation is minimized. (p. 246).

For methane, note that the recommended high alarm level set point would be 40% ~ 60% of the LEL, or between two percent and three percent by volume. The lower value for the high alarm set point, then, corresponds with 30 CFR §27.22(b)(3) which requires automatic shutdown of power at a two percent concentration by volume of methane. Following the guidelines from the chemical processing industry, this would be the more conservative high level alarm point. As Kissel stated in the Handbook for Methane Control in Mining, “Even though methane-air mixtures under 5% are not explosive, worldwide experience with methane in mines has indicated that a considerable margin of safety must be provided” (p. 4).

Writing for *Loss Prevention* on the subject of practical design and operation of combustible gas monitoring systems, and using methane, ethylene, and propylene as examples, Johanson (of Union Carbide) notes:

> Speed of response for a typical application is usually overspecified. Many units provide better service with a two-second time delay which prevents false alarms. Four to six second actuation of a 20% alarm when exposed to 40% LEL material is usually adequate (p.16).

Drawing a direct analogy to underground bituminous coal mining is, perhaps, inappropriate inasmuch as the bits of the cutter head provide an immediate source of frictional ignition—something that would not be present in a chemical processing facility. However, the NEC Class I, Division 1/Division 2 electrical requirements of the hydrocarbon processing industry, and the use of forced ventilation around the obstructions of process equipment is actually very similar to the conditions found at a coal mine working face. Electrical face equipment must be intrinsically safe or permissible, meaning that it must not release enough energy to the atmosphere that would be sufficient to cause an ignition. Were it not for the immediate presence of the ignition source provided by the bits of the cutter head, the presence of methane around permissible electrical equipment would not warrant a more conservative alarm/shutdown approach considering NEC guidelines. The position that the bits on the cutter head are the ignition source of interest is further supported by the sparse number of ignitions caused by electrical equipment arcing at the working face.

Additional support for the threshold level comes from NIOSH's Guidelines for the Control and Monitoring of Methane Gas on Continuous Mining Operations (2010), which states:

> Methane measurements are made on the mining machine to estimate face methane concentrations. Frictional ignitions are most likely to occur at the face where it is not possible to measure methane concentrations during mining. As long as methane concentrations measure on the machine are less than 1%, methane concentrations at the face are assumed to be less than 5%, the lower explosive limit for methane. Whenever concentrations measured on the machine exceed 1%, the protection provided to the worker is reduced (p. 49).

While the type and location of methane sensor is at the discretion of the mine operator (provided that it is an MSHA-approved), guidelines have been developed in a series of Bureau of Mines and NIOSH studies. These will be considered in Section 5. Taylor *et al*. (2001) have said, "Past experience has shown that when methane concentrations on the mining machine are kept below 1.0 pct it is unlikely that any ignition will occur near the face (p. 683).

2.2 Process Characteristics for Gas Monitoring and Process Control

While the threshold level for alarm and shut-down is one consideration for methane concentration monitors, another is the voting scheme used by the monitoring system. Process industry engineers recommend varying levels of redundancy, depending on the hazard/sensitivity combination of the process. Englund and Grinwis, of Dow Chemical Company, consider applications to extensive, computer-controlled processes, such as ethylene oxide plants, lime kilns, and blast furnaces, as well as smaller facilities such as tanker unloading areas. These design concepts are equally applicable in reduced fashion to simpler processes, such as the automatic de-energization of electric face equipment in a coal mine, and the Center for Chemical Process Safety recommends use of a voting rule to initiate a shut-down action.

While the hydrocarbon and chemical industries typically must balance a tradeoff between process operability and hazard sensitivity, this is not the case with electrically powered coal-cutting equipment. First, consider Englund and Grinwis's example of a continuous polystyrene plant. They note that "if heat is lost in the devolatilization section, it will not be possible to forward material through the process. There are only a few minutes during which action can be taken to avoid a runaway and setup of the reactors that can cause loss of the entire reactor system" (p. 40). This is an example of a highly sensitive process. By contrast, de-energizing the cutter-heads on a continuous miner or longwall shearer do not cause any harm to the process of cutting coal. Note that the lack of production when equipment is de-energized does not constitute a process upset, as mining may continue as soon as power is restored. Thus, the coal mining process would be defined as having low process sensitivity. In contrast with high sensitivity processes, Englund and Grinwis recommend for low sensitivity processes, "when in doubt, shut down. There may be some false trips, but the consequences are not severe" (p. 40).

Proceeding from this directive, the question then becomes whether or not the methane monitoring system is appropriately responding to concentrations of methane at, or above, the threshold level, and appropriately de-energizing equipment to avoid methane ignitions. This encompasses location of the monitor, and the voting method employed when multiple sensors are employed, the type of sensors used, and the face conditions. These characteristics of methane monitoring have been investigated by several researchers over the past four decades. Location and sensor type are reviewed in Section 5.

An appropriate voting scheme for a low sensitivity process such as that of bituminous coal mining, therefore, would be to have the automatic de-energization feature engage if one of two sensors detects methane at the threshold level.

3.0 Comparison of Existing Agency Regulations

<u>Aim 2</u>: To compare the West Virginia State Code §22A-2-43, regarding methane at the working face, to regulations of other states and agencies.

In considering the various state laws, and in comparing them to the Federal standard in Title 30 CFR §75.323, it is important to make the distinction between three actions. First is the requirement to de-energize equipment at the working face (or other immediate area). Second is the requirement to disconnect power to the entire affected section. Third is the automatic de-energization of the equipment. Table 1 summarizes various state requirements for de-energizing equipment in the presence of methane, each of which is elaborated upon in the following section. The summary data in this table should be viewed with an understanding that additional information is provided in each of the following sections, since some states allow for operation with increased levels of methane, provided that certain minimum ventilation standards are maintained. Only the MSHA, OSHA, and NFPA regulations address *automatic* shutdown of electrically-powered face equipment. In contrast, manual de-energization and/or disconnect at the source is often specified by the various state agencies, thereby supplementing MSHA regulations. Note also that it may be possible that some operating coal mines program their face machinery to automatically shut down power at the level where their regulations require the disconnection of power. However, only the Federal law, 30 CFR §27.24 requires automatic shutdown, at a level of 2.0 percent methane concentration by volume.

Table 1: Comparison of methane regulations and standards. This table does not contain complete information—clarifications can be found in the appropriate sections for each regulating entity.

Regulating Authority	1.0 percent	1.5 percent	2.0 percent	Exceptions
MSHA				
30 CFR §75.323	De-energize	Disconnect at Source		
30 CFR §27.24			Automatic Disconnect	
OSHA				
29 CFR §1926.800	De-energize & Automatic Disconnect			for TBMs/ gassy excav.
NFPA				
Chapter 4.2	De-energize		Automatic Disconnect	
WV	De-energize	Federal	Federal	X
WV (LW & SW)	De-energize & Disconnect at Source	Federal	Federal	
AL	De-energize	Federal	Federal	
IL	Federal	De-energize	Federal	X
IN	Federal	Federal	Federal	
KY	De-energize	Federal	Federal	
MD	Federal	Federal	Federal	
MO	Federal	Federal	Federal	
NM	Federal	Federal	Federal	
OH (CM)	De-energize	Federal	Federal	X
OH (LW)	De-energize & Disconnect at Source	Federal	Federal	X
OK	Federal	Federal	Federal	
PA	De-energize	Disconnect at Source	Automatic Disconnect	
TN	Federal	Federal	Federal	
UT	Federal	Federal	Federal	
VA	De-energize	Disconnect at Source	Federal	X

While MSHA tends to use the vernacular "methane monitor" for continuously operating machine-mounted monitors and "methane detector" for handheld units, this distinction does not appear to have been incorporated into most state regulations.

3.1 MSHA Federal Regulations

Title 30 of the Code of Federal Regulations, Section 75.323, Actions for Excessive Methane, contains regulations pertaining to the allowable content of methane in intake and return air courses and at the face. At a working place or in an intake air course, when methane levels reach 1.0 percent, ". . . electrically powered equipment in the affected area shall be deenergized, and other mechanized equipment shall be shut off." If methane levels at the working place or in an intake air course reach 1.5 percent, there is an additional requirement to withdraw personnel and ". . . electrically powered equipment in the affected area shall be disconnected at the power source." In both situations, intrinsically safe atmospheric monitoring systems may remain energized.

While the aforementioned regulations apply to the working place and to intake air courses, there are slightly different requirements for return air courses. 30 CFR §75.323(c) concerns that split of return air between the working place on a section and the location where said split of air meets another split of air. In such return air splits, if the methane content reaches 1.0 percent, changes to the ventilation system must be made to reduce the methane concentration to below 1.0 percent. If, however, the methane concentration reaches 1.5 percent, then personnel are to be withdrawn and electrical power in the affected area must be disconnected at the power source.

The "Return Air Split Alternative" of 30 CFR §75.323(d)(1) allows operations to continue under certain conditions: (1) that the greater of 27,000 cfm or that which is specified in the approved ventilation plan is present in the last open crosscut; (2) that methane concentration is constantly monitored with a visual and audible alarm sounding at 1.5 percent; and (3) rock dust is applied continuously, to the return immediately outby the most inby monitoring point during coal production. Note that this applies to the return split and not to the working place but may become applicable at the interface where return air begins.

This can be further recognized when viewing 30 CFR §75.323(d)(2) concerning the "return air split between a point in the return opposite the section loading point" where such split of air meets another. In this case, at a concentration of 1.5 percent methane, personnel are to be withdrawn and, except for intrinsically safe atmospheric monitoring equipment, electric power is to be disconnected at the power source and other mechanized equipment is to be shut off.
In all cases when withdrawl of personnel is indicated, only certified persons may remain to correct the situation via making changes to the ventilation.

In summary, for the working place, the general interpretation is that, at 1.0 percent methane, electrical equipment is to be deenergized and, at 1.5 percent methane, electrical equipment is to be disconnected at the power source. These are actions to be taken, manually, by the mine personnel.

In addition to these regulations, MSHA further includes requirements for permissible equipment operated in "gassy mines and tunnels" with somewhat less stringent methane ranges. These regulations are encapsulated in 30 CFR §27.22 Methane Detector Component and 30 CFR §27.24 Power Shut-Off Component. While the location of the detector is not specified, it is stated that it must either contain a filter element or be kept free from dust which may inhibit its proper functioning. The methane detector must be capable of sounding an audible alarm in the range of 1.0 – 1.5% methane, and in greater concentrations of methane. 30 CFR §27.22(b)(3) requires:

> A method for actuating a power-shutoff component, which shall function automatically when the methane content of the mine atmosphere is 2.0 volume percent and at all higher concentrations of methane.

Note that this level for power shut-off is less conservative than the standards in 30 CFR §75.323 but applies to all sections of the mine, not just the working face. For electrical equipment powered by trailing cables, 30 CFR §27.24(b)(1)(i) permits either the machine alone, or both the machine and its trailing cable to be deenergized by the control circuit actuated by the methane detector component.

3.2 OSHA Federal Regulations

While MSHA regulates mining operations, underground tunneling is regulated by OSHA's Standard for the Construction Industries, 29 CFR §1926. This set of regulations concedes that some excavations, including those bored by rapid excavators, or tunnel boring machines (TBMs), may be gassy. OSHA defines a gassy excavation as one in which an ignition of gas has occurred or, for three consecutive days, 10% or more of the LEL for methane or other explosive gases has been measured at a point twelve inches from the roof, face, floor, or walls of the excavation. In the event that the excavation has been determined to be gassy, certain actions similar to those found in mining operations must be taken.

Specifically germane as a comparison to the MSHA standards, 1926.800(j)(1)(ix) outlines the actions to take if 20% or more of the LEL for methane (or other flammable gases) is found in any underground work area or in the return air course. Under these conditions, employees must be withdrawn from the area according to 1926.800(j)(1)(ix)(A) and

> Electrical power, except for acceptable pumping and ventilation equipment, shall be cut off to the area endangered by the flammable gas until the concentration of such gas is reduced to less than 20 percent of the lower explosive limit,

according to 1926.800(j)(1)(ix)(B). Note that 20% of the LEL for methane is one percent (1.0%).

Additionally, rapid excavators (*e.g.* TBMs) are subject to regulations similar to those for longwall shearers and continuous miners. Section 1926.800(j)(2)(ii) states:

> When using rapid excavation machines, continuous automatic flammable gas monitoring equipment shall be used to monitor the air at the heading, on the rib, and in the return air duct. The continuous monitor shall signal the heading, and shut down electric power in the affected underground work area, except for acceptable pumping and ventilation equipment, when 20 percent or more of the lower explosive limit for methane or other flammable gases encountered.

Again, 20% of the LEL for methane is one percent (1.0%). This regulation is more stringent than that found in the MSHA regulations of 30 CFR §27.22(b)(3). However, unlike bituminous coal mining, there is not the continuous expectation of encountering methane during extraction.

3.3 National Fire Protection Association

The National Fire Protection Association (NFPA), issues the National Electric Code (NEC), the 1968 version of which is referenced by 30 CFR for electrical work in underground coal mines. In addition, the NFPA issues the NFPA 120: Standard for Fire Prevention and Control in Coal Mines, recently revised in 2010.[1]

NFPA Standard 120 contains Chapter 4, "Underground Mining Operations." Section 4.2.2 of this chapter states, "Methane monitors shall be provided on equipment used to cut coal from the face." Additionally, Section 4.2.2.1 states:

> The methane monitors shall alarm at 1 percent concentration and be interlocked to shut down the machine at a 2 percent concentration of methane.

This is nearly the same language of 30 CFR §75.323 and, similar to the MSHA regulation, the type of methane monitoring device and the alarming/shutdown voting scheme are not specified.

Although not pertaining directly to the electrically-powered machinery, it is interesting to note that prior to its adoption, the 2009 Fall Revision Cycle, Report on Proposals included a proposed revision that would add "Section 4.2.10 Methane Control. Methane within the coal mine shall be reduced below 250 ft^3/ton before mining can begin in an area." The Committee action was to Accept in Principle instead the addition of the following text, "Section 4.2.10 Methane Control. Methane within the coal mine shall be reduced to not more than 1 percent on the intake air and 2 percent on the return air." The Committee Statement was:

> The Committee is willing to support the concept for providing requirements for managing methane levels within mines, so they modified the submitter's recommendation as shown. Further research on techniques for appropriate methane control needs to be conducted.
>
> The Committee will consider acceptable solutions for methane control for reconsideration at the ROC meeting by means of a public comment.

Of fifteen votes, eleven were affirmative, one was negative, and three were not returned. One representative, of the National Mining Association, explained his vote against adoption of this requirement:

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[1] In Annual 2004, Standard 123: Standard for Fire Prevention and Control in Underground Bituminous Coal Mines was incorporated into NFPA 120: Standard for Fire Prevention and Control in Coal Mines and NFPA 122: Standard for Fire Prevention and Control in Metal/Nonmetal Mining and Metal Mineral Processing Facilities. NFPA 120 had previously been reassigned to the Committee on Mining Facilities at its formation in 1977, and was formerly known as NFPA 653: Coal Preparation Plants which originated with the 1958 NFPA Committee on Dust Explosion Hazards.

> The new test states that “methane within the coal mine shall be reduced to not more than 1 percent on the intake air and 2 percent on the return air.”   This recommendation is unnecessary as methane concentrations in underground coal mine air courses are already extensively regulated by the Mine Safety and Health Administration (MSHA), see 30 CFR, Part 75.323.

While this comment does not address methane concentration levels at which electrically powered face equipment is to be de-energized, it does address the broader issue of regulation of acceptable methane levels. In short, since the new text of proposed Section 4.2.10 Methane Control was added to the 2010 Revision of NFPA 120 and the text of Sections 4.2.2 and 4.2.2.1 mirrors that of MSHA there is evidently a concurrence between NFPA and MSHA regulations regarding methane safety (in this case from a fire prevention standpoint) in underground coal mining operations.

3.4 West Virginia

West Virginia Code Chapter 22A, Article 2 pertains to underground mines. In §22A-2-43(a) requires that electric equipment shall not be operated in area where methane concentrations exceed one percent methane. Regarding the operation of equipment in working places, §22A-2-43(e) states:

> Indication of gas.—In working places a suitable approved apparatus for the detection of explosive gas shall be provided for use with each mining machine when working, and should any indication of explosive gas in excess of one percent appear on any apparatus used for the detection of explosive gas, the person in charge shall immediately stop the machine, cut off the current at the nearest switch and report the condition to the mine foreman or supervisor.

Power can be restored once the “condition found has been corrected” and so pronounced by a certified person.

The following part, §22A-2-43(f) requires that examinations be made at intervals no less than twenty minutes and, if a one percent concentration of gas is detected, then the “current shall at once be switched off the machine, and the trailing cable shall forthwith be disconnected from the power supply until the place is pronounced safe.”

In some respects, the West Virginia Code is more stringent than the Federal regulations, by requiring that the trailing cable be disconnected at the power supply when methane levels reach one percent. However, this part, §22A-2-43(f), appears to apply primarily to situations where periodic, instead of continuous machine-mounted, methane detectors are employed. Continuous monitors would, then, be subject to §22A-2-43(e), requiring deenergization of equipment at one percent methane, with the Federal standard requiring disconnection at the power source when methane levels reach 1.5 percent, and automatic shut-down at two percent.

Regulations of Title 36, Sections 6 and 7, pertaining to longwall and shortwall mining, respectively, have provisions requiring that an approved methane monitor be installed on the face equipment. In both operations (§36-6-8.1 and §36-7-6.1), this methane monitor "shall give warning automatically when the concentration of methane reaches a maximum percentage of not more than 1.0 volume per centum of methane." The longwall regulation requires installation of the methane monitor at the headgate, with a "censoring" unit installed on the return side of the face inby the rib line.[2]

In both of these regulations, a certified person must make a test for methane no less than once every two hours during the operating shift. Regarding these methane tests, §36-6-8.2 and §36-7-6.2 both state:

> Should one percent or more of methane gas be detected, the electrical equipment shall be immediately de-energized and the electrical power circuit then disconnected from the power supply until the place is pronounced safe by a certified person.

This makes the West Virginia code more stringent than the existing Federal Code.

3.5 Alabama

The Code of Alabama of 1975 contains Section 25-9-82, "Standards and Procedures as to Gases and Air Quality," pertaining to methane in underground coal mines. Specifically, 25-9-82(b) states:

> If the air immediately returning from a split that ventilates any active workings contains more than one percent methane or more, the ventilation shall be improved, and, if it contains 1.5 percent or more of methane, the power shall be cut off from the portion of the mine affected, and the employees shall be required to withdraw until ventilation is improved.

In addition to this, 25-9-82(c) states:

> Face work must be stopped, power to face equipment cut off, and the employees ordered and required to withdraw until ventilation is improved, whenever one percent or more of methane can be detected on an approved type methane detector or whenever gas can be detected on a permissible flame safety lamp at any point not less than 12 inches from the roof, face, or rib. This does not apply to other faces in the entry or slope in which work can be safely continued.

Thus, Alabama requires that face equipment must be de-energized when one percent methane is detected. Additionally, it requires that face equipment must be de-energized also "whenever gas can be detected . . . at any point not less than 12 inches from the roof, face, or rib. With the

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[2] By the description given in the regulation, this is assumed to be a sensor head. Type of methane monitor (*e.g.* catalytic heat of combustion or infrared) is not specified.

exception of the periodic gas monitoring, during production, using handheld devices, this tends to indicate that machine-based methane monitors reading one percent would be the signal to de-energize the face equipment and the Federal standard would apply thereafter. Power can be restored on improvement of ventilation.

3.6 Illinois

In Illinois, 225 ILCS 705/31.04 and 225 ILCS 705/31.05 require that, if the methane concentration at a working face or in a split of air returning from an active working place exceeds one percent methane, ventilation changes must be made to reduce the methane concentration below one percent. According to 225 ILCS 705/31.06, if the methane concentration reaches 1.5 percent methane, in a working place or split of air returning from a working place, personnel are to be withdrawn and ". . . all power shall be cut off from such portion of the mine . . ." until the methane level is reduced below 1.5 percent. Note that these regulations do not address the deenergization of power at methane levels of one percent.

Further, and apparently unique to Illinois, is the exception that allows work to continue at methane levels up to two percent under certain controlled ventilation conditions. 225 ILCS 705/31.06 says:

> However, in virgin territory in mines ventilated by exhaust fans, where methane is liberated in large amounts, if the quantity of air in a split ventilating the workings in such territory equals or exceeds twice the minimum volume of air prescribed in Section 31.02 and if only permissible electric equipment is used in such workings and the air in the split returning from such workings does not pass over trolley or other bare power wires, and if a certified person designated by the mine operator is continually testing the gas content of the air in such split during mining operations in such workings, it shall be necessary to withdraw the employees and cut off all power from the portion of the mine endangered by such methane only when the quantity thereof in the air returning from such workings exceeds 2%, as determined by a permissible methane detector, a permissible flame safety lamp, air analysis, or other recognized means of accurately detecting such gas.

This exception is less conservative than the MSHA regulations, in general terms, but represents a special case which must be incorporated into an approved ventilation plan. Considering the special nature of this exception, the State of Illinois generally requires that power be removed from electrical equipment at methane concentrations of 1.5 percent although Federal regulations require de-energization at one percent methane.

3.7 Indiana

Title 22, Article 10 of Indiana Law contains provisions regulating coal mining. Many sections of this article have been repealed and IC 10-3-1-1, "Definitions" currently states that "mining law" encompasses (1) this Article 10; (2) IC 22-1-1-5(a); and (3) 30 CFR part 75. What remains of Article 10 is largely concerned with filing requirements, such as with mine maps. Section 5(a) of

IC 22-1-1 provides the scope of powers and duties for the [Indiana] Bureau of Mines and Mining Safety. In the absence of any specifically defined safety standards regarding methane, Indiana reverts to 30 CFR §75.

3.8 Kentucky

Chapter 352, Mining Regulations, Section 232 Definitions—Safety Requirements Governing Use of Electrical Face Equipment—Examination for Methane Gas, Part (2), requires that electrical face equipment may not be brought into a section if methane concentration levels exceed one percent. In a working place, 352.232(3) requires that examinations for gas be made at least every 20 minutes while equipment is operating and says,

> If methane gas is found in excess of one percent (1%) at any time, the power shall be de-energized from the equipment and left de-energized until the gas is reduced to less than one percent (1%) and the place determined safe by a foreman.

This indicates that Kentucky requires deenergization of electrical face equipment when methane levels reach one percent. This would be the same as the Federal requirement, which would also require that the power be disconnected at the source if methane concentration levels reach 1.5 percent. These Kentucky regulations became effective July 13, 2004.

3.9 Maryland

The Unannotated Code of Maryland and Rules, Title 15 Mines and Mining, Subtitle 4, Rules and Regulations Governing Mining Activity sets forth regulations for permitting and defines the roles of mine employees. Section 15-404, Protection and Safety of Mine Employees does not contain any references to methane nor ventilation. As such, Maryland falls under the Federal standard, 30 CFR §75.

3.10 Missouri

Missouri Revised Statutes, Chapter 293 Mining Regulations, requires under 293.120(4), Air Safety Requirements, that air must be improved if methane exceeds one percent. According to 293.020, this chapter is applicable to all mines in Missouri, except barite, limestone, marble or sand and gravel. For underground bituminous coal mines, Missouri must rely on the Federal regulations pertaining to methane.

3.11 New Mexico

The Annotated Statutes of New Mexico, Chapter 69 pertains to mines. Article 20, Ventilation and Gases in Coal Mines, along with many other Articles pertaining to underground coal mine safety were repealed by Laws 1987, ch. 234 §84. Most of the remaining regulations concern filing requirements. New Mexico 69-8-16, Underground Mine Safety Regulations; Penalties, contains the language "In addition to requirements pursuant to Federal Law for underground mines . . ." and includes several small requirements, none of which pertain to methane. New Mexico, then, is defaulting to 30 CFR §75.

3.12 Ohio

Ohio Chapter 1567 Division of Mineral Resources Management—Mines and Quarries contains 1567.73 "Methane monitors; safety examinations of working face" containing specific regulations on methane. Part (A) of this regulation requires the installation of a methane monitor on all longwall faces capable of automatically warning a condition where one percent of methane is present. The location for this monitor must be specified by the mine on an approved plan or revision thereof as required by 1567.69 of the Ohio Revised Code, for which 1567.73 (B)(9) and 1567.73 (B)(10), are the ventilation plan and methane control plans, respectively. Should the methane monitor malfunction, electric equipment cannot be operated longer than ten minute intervals without checking manually for methane gas. Additionally, methane checks must be made hourly on the intake side of the longwall working face. Under normal operation of the methane monitor, 1567.73(B) includes:

> If one per cent or more of methane gas is detected along the coal face, the electrical equipment shall be immediately de-energized and the electrical power circuit then disconnected from the power supply until a certified person pronounces the place safe.

Thus, Ohio is using a one percent standard for longwall operations, including disconnection from the power source. Methane regulations not specific to longwall operations are contained in Ohio Revised Code 1567.09 Ventilation of Mines. Any air immediately returning from a split must contain less than one and one-half percent of methane. If not, this regulation requires withdrawl of employees from the mine, or portion thereof, and de-energization of all power to the affected section until ventilation is improved. If the methane levels exceed one and one-half percent but are less than two percent, withdrawl of employees and de-energization of power is not required if certain conditions are met. These include a minimum air volume of 18,000 cfm, that all electrical equipment is permissible, that bare wires (e.g. trolley wires) are not present, that no blasting is performed, and that continuous methane monitoring is performed by a qualified person, and that:

> When the methane content of air in face operations exceeds one per cent at any point twelve or more inches from the roof, face, or rib, as determined by a permissible methane detector, a permissible flame safety lamp, or analysis, such condition shall be corrected by improving the ventilation promptly. The electric face equipment at such point shall be turned off and not turned back on until the methane condition is corrected by improving the ventilation.

While the aforementioned exceptions of 1567.09(D) seem to imply that operations can continue with methane levels exceeding one percent, it should be noted that these are exceptions are for return splits. The last exception applies specifically to the working face and requires that electric face equipment be de-engerized at methane levels of one percent.

Therefore, the one percent standard for de-energization of face equipment applies to both longwall and continuous miner sections in the State of Ohio, with the longwall sections additionally requiring that power be disconnected at the supply. Uniquely, Ohio also requires that the location of methane sensors on the longwall equipment be included in the mining plan and that these sensors automatically alarm at one percent methane.

3.13 Oklahoma

The Oklahoma Administrative Code, Title 460, Department of Mines, Chapter 15 applies to Underground Coal and Asphalt. Ventilation at the face is addressed in §460:15-1-25(k) insomuch as the regulation says, "All mines liberating any dangerous, explosive or noxious gases shall be kept free of standing gas in all working places and roadways." However, the subject of actions to take at specific concentrations of methane is not addressed. Therefore, the Federal regulations would be applied for Oklahoma.

3.14 Pennsylvania

Act 52, SB 949 Session of 2008 revised the Safety Laws of Pennsylvania for Underground Bituminous Coal Mines; these changes became effective January 3, 2009. The Pennsylvania Laws closely adhere to the Federal regulations contained in 30 CFR §75.323. According to Section 230 Ventilation Requirements, in a working place or intake air course, including those in which belt conveyors are installed, if methane levels are detected at one percent, Title 52 §230(d)(2)(i) requires that all electrically powered equipment, except intrinsically safe atmospheric monitoring systems, be deengerized. Personnel may not perform any work until the methane level is reduced below one percent. Title 52 §230(d)(2)(ii) provides for the withdrawl of personnel and disconnection, at the source, of electrically powered equipment (except intrinsically safe atmospheric monitoring equipment) if methane concentration levels reach 1.5%. Requirements mirroring those in the Federal regulations are applied for return air courses.

Electrical Regulations are found in Section 316, with Subsection (i) pertaining to methane monitors. Section 316(i)(2) states:

> When the methane concentrations at any methane monitor reach 1%, the monitor shall give a warning signal. The warning signal of the methane monitor shall be visible to the mining machine operator, who can de-energize electric equipment or shut down diesel equipment on which the monitor is mounted. A gas check shall be completed in accordance with this act if at any time the methane concentrations at any methane monitor reach 1.5%. This shall only apply if the methane monitor maintains a warning signal for methane concentrations of 1.5%.

Under this regulation, a scenario would have the operator manually de-energizing the coal cutting machinery upon seeing a concentration of 1.0% methane displayed on a readout for the machine-mounted methane sensor. At a concentration level of 1.5%, the State requirements of Title 52 §230(d)(2)(ii) and the Federal requirements of 30 CFR §75.323 provide for disconnection of the power at the source.

Furthermore, under Section 316(i)(3),

> The methane monitor shall automatically de-energize electric equipment or shut down diesel-powered equipment when the methane accumulation reaches 2% or the methane monitor is not operating properly.

Essentially, with this language Pennsylvania has also enacted its own version of 30 CFR §27.24 and NFPA 4.2.2.1.

It is worth noting that these revisions supersede older language from Section 316(h)(1), in Electrical Face Equipment, which said:

> In working places where explosive or noxious gas is likely to be encountered, an approved safety lamp for the detection of such gas shall be provided for use with each machine when working, and should any indication of gas appear on the flame of the safety lamp, the person in charge shall immediately stop the machine, cut off the current at the nearest switch, and report the matter to a mine official.

This older version did not specify nominal methane concentration levels, meaning that the Federal regulations took precedence. In viewing the current regulations of the Commonwealth of Pennsylvania, it appears that the Federal standards have been adopted—that is, at 1.0% methane, equipment is de-energized; at 1.5% the power must be disconnected at the source; and, at 2.0% an automatic de-energization must be initiated.

In addition, Pennsylvania is one of the few states to specify acceptable locations for methane monitors. Regarding longwall operations, Section 316(i)(1) says, in part, "The sensing device for methane monitors shall be installed at the return end of the longwall face. An additional sensing device shall also be installed on the longwall shearing machine, down wind and as close to the cutting head as is practicable." For all other machines, the regulation is to install the methane sensing devices ". . . as close to the working face as is practicable." This regulation captures the essence of the recommendations reviewed in Section 5.2 and mirrors 30 CFR §75.342.

3.15 Tennessee

Title 59, Chapters 5 and 6, Regulation of Mines Generally and Commercial Coal Mines, respectively, have been repealed. In consideration of the absence of any specific regulations concerning methane, Tennessee reverts to Title 30 CFR §75.

3.16 Utah

Title 40 of Utah Code, Mines and Mining, contains the Coal Mine Safety Act in Chapter 2. Section 301 of this Title and Chapter delineates the responsibilities of the Commission and Office of mine safety. Under 40-2-30(3)(c), the Commission is to "establish a cooperative relationship with the Mine Safety and Health Administration to promote coal mine safety in Utah." This Coal Mine Safety Act does not specifically address methane nor ventilation and, for electrical issues, requires compliance with 30 CFR 75.152 for underground operations, under Utah 40-2-402(D). As such, Utah incorporates the methane regulations set forth in 30 CFR §75.

3.17 Virginia

The Code of Virginia, Title 45.1, Mines and Mining, Chapter 14.3, Requirements Applicable to Underground Coal Mines is similar to the Federal standards regarding actions to take for excessive methane concentrations. Section 45.1-161.222(B) Actions for Excessive Methane requires that electrically powered equipment be de-energized, except for intrinsically safe atmospheric monitoring systems, if methane concentrations reach one percent in any working place, intake air course, or belt entry. Personnel may remain, only to reduce methane levels below one percent. If methane levels reach 1.5 percent, Section 45.1-161.222(C) requires withdrawl of personnel and "Electrically powered equipment in the affected area shall be de-energized and other mechanized equipment shall be shut off except for intrinsically safe atmospheric monitoring systems (AMS)." In a return air split coming from a working face, Section 45.1-161.222(E) requires power to be de-energized at the source if methane levels reach 1.5 percent. Work can continue in the area with up to 1.5 percent methane if a minimum 27,000 cfm is maintained in the last open crosscut, per Section 45.1-161.222(F).

Thus, in Virginia, the requirement for both one percent and 1.5 percent methane is to de-energize the electrically powered equipment, but the law does not require disconnection at the power source for the 1.5 percent concentration level unless detected in the return air course coming from the working place.

4.0 Methane Ignitions and Electrically Powered Equipment

<u>Aim 3</u>: To characterize the hazard associated with the interplay of electrically-powered face equipment and methane ignitions.

To determine the value inherent in de-energizing electrically powered face equipment at a threshold level of methane concentration, it is necessary to ascertain the reason(s) why such action would be beneficial. In other words, determining the main causes of methane ignitions is the first step to preventing methane ignitions.

4.1 Causes of Methane Ignitions

Several studies, over the past fifty years, have investigated the causes of methane ignitions and other mine fire phenomena. An objective review of this literature supports the position that frictional ignitions at the face, and not the prevalence of electric-powered equipment, *per se*, is the root problem. As early as 1965, before the act that established MSHA but after electrification of mines was common, summarized statistics showed that friction at the cutter head was responsible for ninety percent of the ignitions (Blickensderfer, 1972, p. 2). As noted more recently by the Fire Protection Handbook, 17th Edition, published by the National Fire Protection Association:

> About 5 percent of underground coal mine ignitions and explosions result from electric arcs. This figure is surprisingly low in view of the extensive used of electrical equipment in underground coal mine face areas and the low electrical energies required to ignite methane. (p. 8-176)

Their data is sourced from Nagy (1981) and covers the period 1970-1977. During this period, there were 285 frictional ignitions, comprising 85% of the total. It is important to recognize none of the ignitions listed were further partitioned to identify occurrence locations at the face or in some outby location—a fact highlighted by the high percentage attributed to burning and welding operations. Thus, while it is probable that most of the electrically-induced ignitions did not occur at the working face, it is also likely that some of the 285 frictional ignitions were caused in outby areas, such as on belt lines.

This contrasts with the 1960s and 1970s where fully 40% of coal mine fires could be traced to an electrical origin, with half of these caused by faults in electrical trailing cables powering face equipment. The NFPA notes that conversion from DC to AC powered equipment significantly reduced this percentage (pp. 8-174 to 8-175). This level, as noted above, had been reduced to approximately five percent in 1991.

To overcome the limitations of the data available, in 1995, Schatzel segregated those ignition events that were associated with machinery (that did not list other causes, such as a known electrical problem) by co-analyzing the MSHA ignition data with the equipment descriptions in the (former) Health and Safety Analysis Center database and found a 100 percent correlation when randomly testing this method of characterization. Moving forward, Schatzel created a frictional ignition database that also included information on production, working conditions, and coal mine methane emissions. Analyzing the period 1980-1992, Schatzel found that, "Coal production did not show a strong correlation to frictional ignitions. However, a correlation was observed between *high rates of production increase* and frictional ignitions" [emphasis added]. While production was not a significant correlate, the type of mining machinery was, with continuous mining machines outdistancing all other mining methods for the largest number of frictional emissions over the study period. Roof bolters had the lowest percentage for frictional ignitions and this was proposed to be the result of better ventilation in those areas where the bolters operate. Although complete data was not available, another apparent inference is that frictional ignition events are more prevalent in gassy mines than in non-gassy mines, independent of whether or not these mines are in the same coal seam. The upshot of the Schatzel article is that frictional ignitions do not appear to be correlated with production.

In 2006, another review, "Frictional Ignitions in Underground Bituminous Coal Operations 1983-2005," shows that the same trends continue. Krog and Schatzel say that the majority of all ignitions in underground coal mines are due to friction. As compared with the Schatzel study, Krog and Schatzel also found that continuous miners were responsible for the majority of frictional ignitions, representing 1,090 of 1,589, or 68.6% of all ignitions. Longwall shearers comprised 383 of the ignitions, or 24.1%. Together, continuous miners and longwall shearers account for 92.7% of the frictional ignitions, as shown in Figure 1. Roof bolters add another 3.1%, with 50 out of 1,589 occurrences. The remaining causes are distributed with 20 (1.3%) in unknown equipment, 23 (1.4%) in other equipment, 19 (1.2%) in cutting machine varieties which do not appear after 1990[3], and 4 (0.3%) for ground falls. The importance of this review is the recognition that frictional ignition, not electrical arcing, is the primary cause of methane ignition.

Krog and Schatzel further explored the data, finding the same as Schatzel that production at any given mine was not correlated to the prevalence of frictional ignitions of methane. They did say, however, that, for a given seam, the production of the total seam was positively correlated with the frequency of friction-induced methane ignitions. Further, Krog and Schatzel presented that longwall operations had a higher frequency of frictional ignitions than room-and-pillar operations. This was attributed to the necessity of having continuous miner sections cutting gateroads, the latter becoming better ventilated and degassed by the time the longwall commences. Another insight was that 75.5% of the total number of frictional ignitions occurred in three states: Alabama (710), Virginia (247), and Pennsylvania (242). Parsed by coalbed, Central and Northern Appalachia, which includes West Virginia, combine to represent 42% of the total, with the Warrior Basin exceeding them at 44.7%. The remaining coalbeds represent less than 10% each. The State of West Virginia reported 8.3%, or 132 of the 1,589 frictional ignitions 1983-2005. Figure 2 depicts this data.

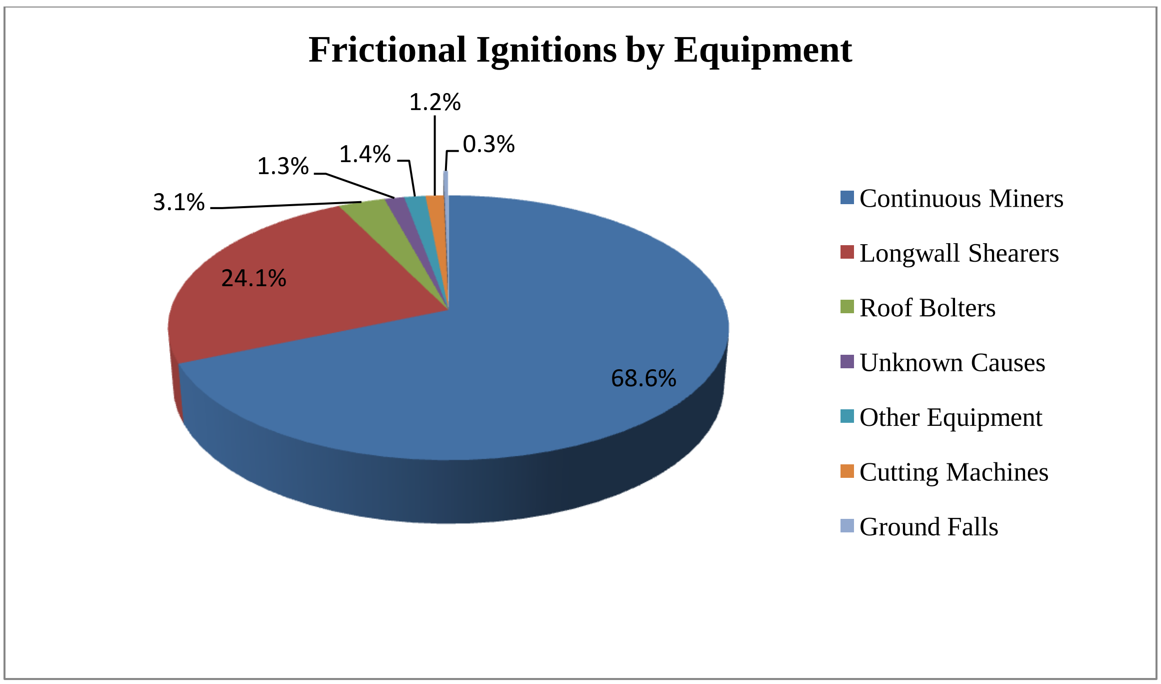

Figure 1: Distribution of frictional ignitions by equipment type, 1983-2005. Data from Krog and Schatzel, 2006.

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[3] Primarily equipment used for drill and blast operations.

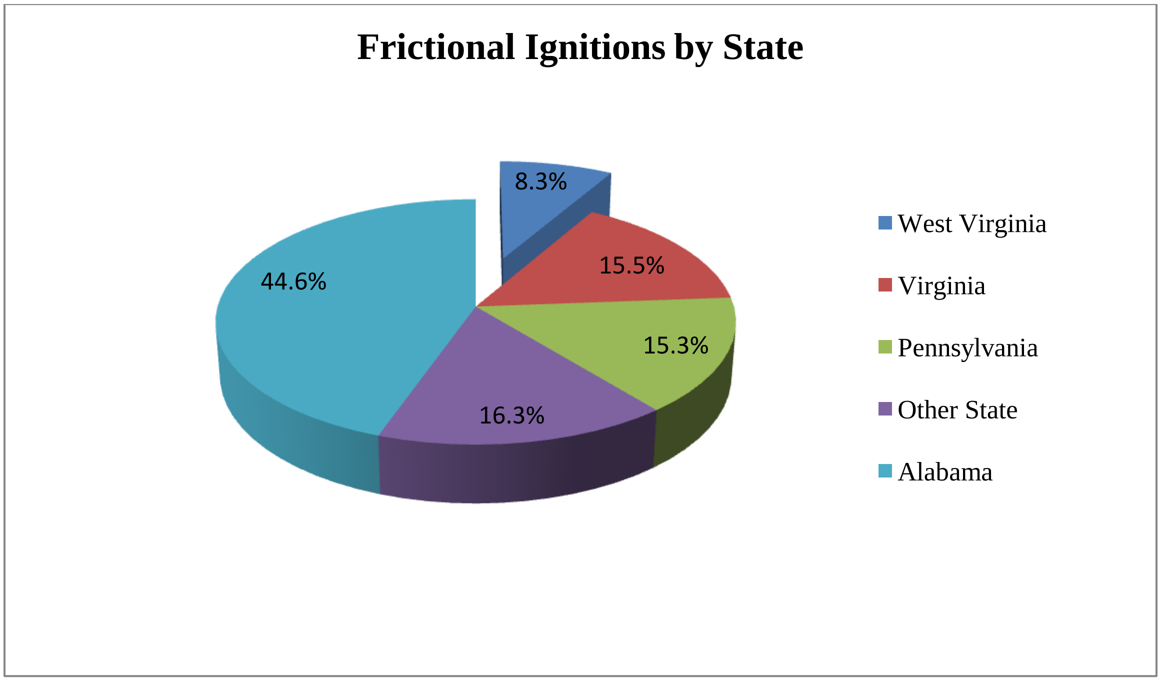

Figure 2: Frictional ignitions by state, 1983-2005. Data from Krog and Schatzel, 2006.

4.2 Ignitions from Roof Bolters

Regarding methane ignitions by roof bolters, both Urosek and Francart (1999) and Taylor *et al.* (1999) have reviewed MSHA roof bolter ignition reports. For the period 1981-1998, the distribution of ignition sources is as shown in Figure 3. Ignoring, for the moment, electrical and unknown causes, the remaining 92% of bolter ignitions can be attributed to frictional sources. Electrical causes comprise only 3% of the total.

Thus, similar to continuous miners and longwall shearers, the primary source of ignitions originates with friction, often caused by dulled cutting bits, and not by arcing of electrical equipment. An automatic shutdown on roof bolters would only be effective if, in the presence of a frictional ignition source, the arresting of drilling would remove this source of heat. Methane ignitions in drill holes usually occur at the roof interface where methane from the hole mixes with air to a flammable composition. Therefore, one would assume the methane monitor that is designed to cause an automatic shutdown would best be located at the hole. However, a study by Talyor *et al*. in 1999 found existing monitor locations sufficient and cautioned that additional testing should be performed to establish the relationship between methane released at the drill hole and that at machine and sweep locations. They conclude with “Methane sampling locations should not be changed unless it can be demonstrated that the change provides the same or greater level of safety for the worker” (p. 178).

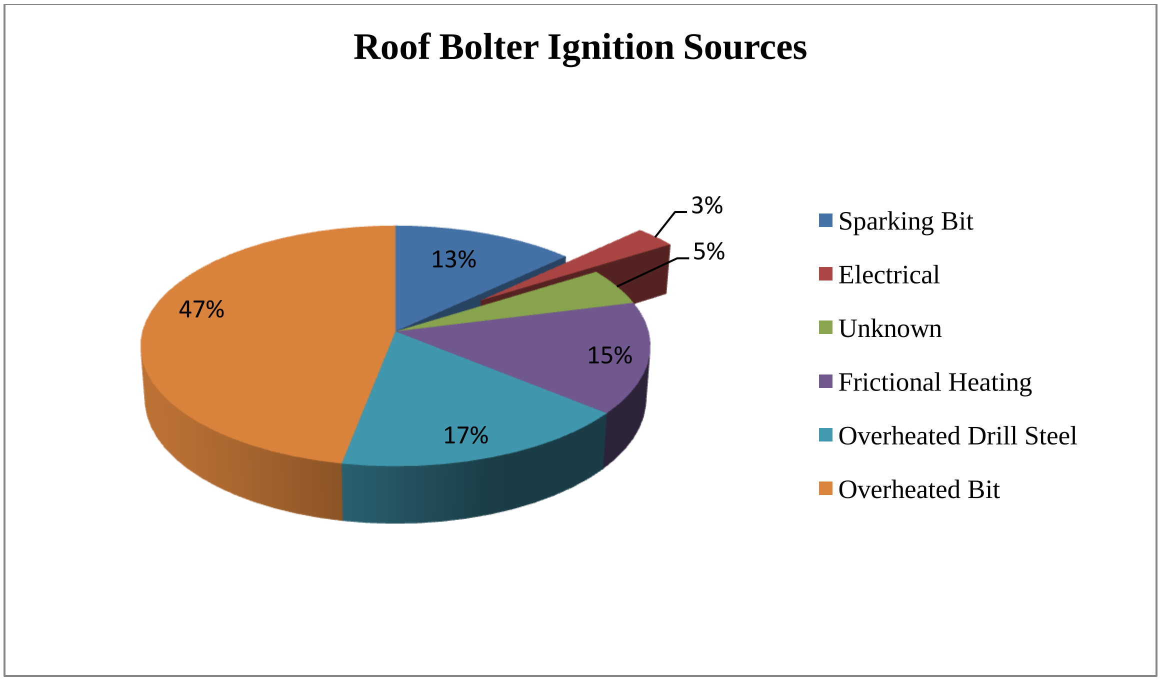

Figure 3: Roof bolter frictional ignitions 1981-1998. Data from Urosek and Francart, 1999.

4.3 Synopsis of Ignition Mechanism

The literature concerned with frictional ignitions concentrates on the prospective that, to reduce the probability of methane ignitions at the face, the source of frictional ignition must be controlled. Along with degasification of the coal seam, the focus is on ventilation, bit selection, and various arrangements of water sprays (see Thakur, 2006). Admittedly, these methods are intended to reduce the occasions of frictional ignitions while maintaining production. Notable by its absence is the concept of de-energizing electrical power to the cutter head to stop rotation and, thereby, eliminate the possibility of a friction ignition.

In 1990, Courtney observed, "The present observation that a lower bit velocity did not appreciably decrease the likelihood of frictional ignition with a worn bit until a very low velocity was used does not agree with previous studies." He mentions some of the possible reasons for this disparity but concludes, "However, the present results indicate that a lower bit velocity probably is not a reasonable alternative to avoiding frictional ignition with worn bits in a practical mining operation" (p. 19). This contrasts with earlier recommendations from a 1974 study by Blickensderfer *et al.*, where various combinations of rock and cutting bit material were compared and it was proposed that the cutting speed should be limited to 300 fpm (p. 16). It was advised that the rate of advance could, instead, be increased to maintain "current production levels."

Note that studies of bit-induced frictional ignitions, both prior to and subsequent to the Courtney study, focus especially on the greater likelihood of worn bits, versus new bits, creating a sustained hot streak on material such as sandstone, with sufficient area to transfer enough heat for ignition. Courtney says "From a more fundamental viewpoint, the ignition of a methane-air mixture by a hot surface depends upon the temperature and area of the hot surface and the exposure time" (p. 19). This statement is reinforced by the same study by Blickensderfer *et al.* in which the authors say:

> At one time, the sparks produced by frictional rubbing or impact were believed to be the source of frictional ignitions of coal mine gases. However, early investigations by SMRE[4] showed that the sparks themselves were not generally responsible for the ignition of air-methane (p. 2).

These early investigations date to the late 1920s in England and thereafter also consumed many research hours of the U. S. Bureau of Mines. To once again quote Blickensderfer *et al.*:

> To initiate a methane explosion, a minimum combination of time, temperature, and surface area of a source are required in order to heat the necessary minimum volume of gas to a sufficient temperature (p. 2).

For these reasons, showers of sparks, especially when cooled with water sprays, are unlikely to ignite methane. A study by the U. S. Bureau of Mines, investigating incendivity and abrasion sparks was forced into using a hydrogen-air mixture after a 7.4% methane-air mixture failed to ignite. The inability to ignite the methane-air mixture was repeated for most of the cutter bit alloys that were being tested before the researchers resorted to changing the fuel gas to hydrogen in order to promote ignitions to study (Blickensderfer *et al.*, 1972, p. 8).

The combination of time, temperature, and surface area has been studied from various perspectives, mostly related to cutter bit design or the question "how worn is worn?" but the upshot of all these studies, from a practical operating standpoint, continues to be that worn bits need to be replaced to lessen the probability of creating an ignition source for methane. Similarly, other studies have focused on ventilation to control methane and prevent the minimum volume from accumulating near a location where worn cutter bits may be leaving hot streaks on non-coal rock. The non-coal rock most frequently used for these ignition tests is sandstone. In the 1974 study, Blickensderfer *et al.* considered quartzitic sandstone, silty sandstone, limestone, and sulfur balls. Sulfur balls and limestone did not produce any frictional ignitions. They concluded,

> Sandstone appears to be the real culprit in causing ignitions. Bureau experience has shown that ignitions are not started from frictional sparks but are always caused by a "flashing" phenomenon associated with a frictional hotspot that develops on the sandstone (p. 8).

The combination of excessive methane and the presence of sandstone have been called the "two common denominators" of frictional ignitions by Thakur (2006). This combination likely accounts for the larger prevalence of frictional ignitions at the cutter heads of continuous miners and longwall shearers versus roof bolters or other equipment.

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[4] SMRE is the Safety in Mines Research Establishment of Sheffield, England.

One other result of the Bureau of Mines studies is that the hotspot developed very rapidly in the laboratory tests, in about two milliseconds, whereas cooling took twenty times this, or forty milliseconds. Hotspot temperatures ranged between 1,200 ºC and 1,400 ºC, or an order of magnitude greater than the 150 ºC exterior temperature of electrical boxes as permitted under Federal regulations.

Continued research on methane ignition at the face focuses on frictional ignition as the primary source (Taylor *et al.*, 2010; Kissel, 2006; Thakur, 2006).

5.0 Performance of Methane Monitoring Systems

<u>Aim 4</u>: To assess the capabilities of machine-mounted sensors with regard to their ability to detect levels of methane and cause an automatic process shutdown (*i.e.* de-energize power to mining operations).

Historically, there have been many improvements in methane monitoring during this period, so that the sensitivity of the sensors and their response time continues to be a less critical issue. For example, the introduction of digital communication schemes has made an improvement in response times versus some early analog models that required calculations to be performed in a separate bridge circuit and had to be field calibrated based on the length of wire between the sensor head and the monitor circuit. This technology was emerging in 1986 when Kissell *et al*. performed their study of methane monitors and the probability of face ignitions based on a number of the aforementioned characteristics. While primarily concerned with continuous miners, the approach and results of their study continues to be applicable to modern mining methods and will herein serve as a start point for discussion. Their premise was that, if a frictional ignition occurs, then the methane monitor (thereafter checked and found to be fully functional) must have failed to respond appropriately to the methane encountered due either to monitor location or to monitor response time (p. 49-50).

Methane monitors were first used on face equipment in the late 1950s, following a U. S. Bureau of Mines program to develop continuous monitors for such purposes in 1958 (Taylor *et al.*, 2010, p. 5). As research has continued to reduce methane concentration and sources of ignition, this research continues to cite, not challenge, the existing regulations for alarming at one percent and automatic de-energization at two percent methane by volume.

The performance topic is that which is, perhaps, most open to interpretation inasmuch as coal mines generally specify the type and location of methane monitors to be included on the equipment that they purchase from the manufacturer.[5] That being said, recognize some studies have been performed to determine the optimal location for methane sensors on both continuous miners and longwall shearers. Further, earlier studies that were performed considered methane monitoring equipment that was less robust than that currently in use. Still, the concepts

[5] 30 CFR §75.342 requires only that "the sensing device must be installed as close to the working face as practical." Pennsylvania Title 52 Section 316(i)(1) is similar, and Ohio requires that the sensor locations for longwall shearers be included in mining plans submitted to the State.

concerning methane monitor location and methane monitor response time are applicable to today's machinery and there is always the possibility that some mines are using older equipment that has yet to be retrofitted with more modern sensors. More recent research tends to support the earlier research and NIOSH has developed preferred locations for methane monitors on typical coal-cutting machinery, including roof bolters. Continuous miners and longwall shearers will be discussed in this section.

5.1 Methane Monitoring & Sensor Types

Federal (and State) regulations do not incorporate required response times for methane monitors (Taylor, 2002, p. 315). In Sections 2.2 and 5.0 it was noted that the methane sensors originally employed on electrically-powered face equipment have been improved since the time that they were originally employed. Two types of sensors are prevalent.

Most earlier monitoring schemes, and many of those currently in use, employ a catalytic heat of combustion sensor with a separate bridge circuit. The following explanation from General Monitors Corporation provides an explanation of the principle of operation:

> Based upon the simple principle that as combustible gas oxidizes it produces heat and the sensor converts the temperature change via a standard Wheatstone Bridge-type temperature transducer to a sensor signal. The sensor components consist of a pair of platinum heating coils embedded in a catalyst. Since the reactants are all gaseous, the reaction takes place on the surface of this element with the gases reacting exothermically with oxygen in the air to raise its temperature. This results in a change in resistance within the embedded coil, which is linearly proportional to gas concentration (p. 2).

While these time-honored sensors have been in use for over four decades and have fairly fast response times, note that they require oxygen for their operation. In addition, the catalysts can become contaminated by the presence of various substances, degrading sensitivity to the point of inactivity. Prolonged exposure to high concentrations of combustible gas can also degrade performance.

Although comparatively less infrared detectors have been approved for use by MSHA, they are increasingly being considered. Infrared radiation, at specific wavelengths, is absorbed by certain gases, particularly hydrocarbons such as methane, when passing through a volume of gas. Infrared sensors compare absorbed radiation between a source and a detector for both the sample and a standard. They are specific to a particular gas, such as methane, and do not suffer from degradation of the catalyst due to poisoning or overexposure to high concentrations of combustible gases. They are, however, susceptible to dusty environments and environments where high humidity is present. Their optical windows must be kept clean for proper functionality.

The research cited in sections 5.2 and 5.3 expands from that conducted with catalytic sensors to newer, infrared sensors—both can provide reliable readings when properly maintained. In the Kissell *et al.* study, in 1986, at least one digital methane monitor was tested. Note that one aspect of the study was to improve the response time of the existing analog sensors. One of the attempts to improve the sensors was to add a lead circuit to it, and this did improve the response time somewhat. Of the digital sensor, the authors say, “The evaluation was similar to that of the other monitors. Response was slightly faster than the response using the lead circuit” (p. 54). This can be taken as representative of, what was then, one upcoming technology.

It has been mentioned that one advantage of the digital sensor is that calculations are performed at the sensor head, instead of with a bridge circuit located in a box somewhere else on the equipment. This alleviates the need to calibrate for the resistance of wires between the sensor and the bridge circuit.

Comparisons of infrared absorption sensors with catalytic heat of combustion sensors have been undertaken by NIOSH. In one test, two infrared and one catalytic sensors were compared for response time with the two infrared sensors having a response time of 10 and 33 seconds respectively, and the catalytic sensor between them with a response time of 19 seconds (Taylor *et al.*, 2010, p. 48). Like the catalytic sensors, the infrared sensors have a negative correlation between response time and cleanliness of the sensor head.

Whether a catalytic heat of combustion or infrared absorption sensor is used, the conclusion of all this research shows that proper maintenance of the sensors themselves (*e.g.* cleanliness) is the greatest controllable variable for coal mine operators. Response time should be viewed along with a one-of-two voting scheme as described in Section 2.2.

5.2 Continuous Miners

Kissell *et al*. performed a study on methane monitors for continuous miners in 1986 using a full-scale model mine. In Section 2.2 the use of two sensors for monitoring was advocated. Important in the Kissell *et al*. study was the recognition of using two monitors with a voting scheme that would (in an actual situation) shut down the machine if either of the two sensors attained the threshold concentration. The study, however, considered each of two methane monitors separately to determine overall system robustness. In addition to using four methane monitors approximately twelve inches[6] from the face to determine an average face methane concentration, the following approach was used:

> One measurement with the “brattice-side monitor” was made on the brattice side of the heading, to simulate readings with the brattice and monitor on the same side. The second measurement with the “off-side monitor” simulated the brattice and monitor on opposite sides. Of these two monitor readings, the higher was called the “high-side monitor” to represent a hypothetical dual-head monitor that has heads on both sides of the machine from which it selects the higher readings (p. 50).

Concentration ratios were determined for each of 26 tests, with the machine positioned to represent a standard mining sequence. These ratios compared, for example, the high-side

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[6] The study used the Metric system, with a distance of 0.3m, or approximately 12 inches. This distance is commensurate with requirements for taking handheld methane readings at the face.

monitor to the face average and, for another example, the off-side monitor to the face average. By using concentration ratios, a statistical analysis of efficacy could be performed. Results were normally distributed, but the standard deviation was large. The high-side concentration ratios varied from about one-third the face average value to twice the face average value.

Brattice-side concentration ratios were less than the face average, at 0.77 and off-site concentration ratios were less than the face average, at 0.80. However, the high-side monitor had a concentration ratio of 1.1. Thus, the high-side monitor gave a higher reading than the average face reading. In the voting scheme of letting the highest monitor reading cause a shutdown (sometimes called a "peak-picker" scheme), the methane monitor would have de-energized the machine when the methane concentration was actually lower than the setpoint.

Using the statistics, it was determined that the high-side monitor had a concentration ratio of 0.5 (or half the face concentration) only 9% of the time, and that the monitor will "frequently give readings higher than the face concentration, which may lead to unwarranted shutdowns." The authors continue, saying that, "We may arbitrarily select 2.0 as the concentration ratio above which unwarranted shutdowns occur. This value of 2.0 was chosen because it is the reciprocal of 0.5, the value selected to indicate that the monitor was not measuring the face concentration properly." Under this scenario, the concentration ratio is less than 2.0 for 97 percent to 99.8 percent of the tests, corresponding to an unwarranted shutdown rate of 3 percent to 0.2 percent, respectively (p. 51). Note that the value of 2.0 herein refers to the concentration ratio, not the concentration of methane.

The researchers then investigated the response time of the monitors, considering three variables: sample velocity, dust shield design, and condition of shield. Sample velocities were chosen based on typical mining ventilation conditions. As the sample velocity increased, the time required for machine shutdown decreased, when the sensor heads were exposed to five percent methane. However, when dust shields with intricate paths were installed, and the sample had to diffuse through such paths, response time increased. The condition of the shields was also important. Kissell *et al*. elaborate:

> Tests with contaminated shields showed a degradation in response time due to the presence of dust and water. Here the critical factor was the time required for the monitor to display 2 per cent when subjected to a 5 per cent mixture of methane. Depending upon the monitor and filter used, the dust and water could increase the lag time from a minimum of 14 per cent to instrument malfunction.

The authors further concluded that:

> . . . the available dust shields could not be markedly improved without making the monitor more vulnerable to failure due to dust or water accumulation on the shield. More importantly, although dust and water shields added to the total response time of the monitor, the time was not very significant compared with the lag time when the shields were not used.

It is important to recognize that, at the time of this research in 1986, there was considerable interest in improving the response time of methane monitoring equipment, and this research used monitors that were available and in use at the time. Times to display two percent methane, when five percent methane was introduced[7], varied on clean shields from 2.9 seconds to 10.5 seconds, depending on the sample velocity and monitor type.

Building on this research and with a recognition that deeper cuts would affect the methane liberation characteristics of continuous mining, NIOSH has undertaken a number of studies which are summarized in Information Circular 9523, published in 2010.

Regarding location, Taylor *et al.* (2001) state that "Where the methane monitor is located on the machine is one of the most important factors for that determines how effectively face methane levels can be predicted" (p. 2). To comply with the current setpoints (1% warning and 2% automatic shut-down), the researchers propose equations to correct face methane levels for various locations of the methane sensors on the machine. They use a "best straight line" estimate for a scatter plot of methane readings at sensor locations versus the face concentration, as determined from experiments on a full-size model at NIOSH. They say, "The straight-line model is the simplest one for comparing the data and there was no reason to believe a more complex model would fit the data better" (p. 3). While the concept has merit, it should be noted that the authors did not use certain advanced, albeit relatively simple, statistics to test for the influence of potential outliers on their regression lines.[8] Furthermore, neither data splitting nor any other method to validate the efficacy of the equations for making predictions was employed. Thus, they correctly recommend, for the safety of personnel, that any equations developed should be field verified prior to any implementation.

In summary, relying on decades of research, NIOSH recommends the following guidelines for placement of methane monitors:

- Six to 8 ft from the face where damage to the head due to falling rock and moisture is less.

- On the return air side of the mining machine (side opposite the ventilation tubing or curtain) where methane concentrations are usually highest (Taylor *et al.*, 2010, p. 49).

For the return air side, the authors provide additional information which would also be of interest to a mine operator having a continuous miner manufactured for their operation (see also Taylor *et al.*, 2001 and 2004).

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[7] As a step input.

[8] It is assumed from additional information in the paper that the "best straight line" estimate refers to an attempt at a linear regression, although the term "linear regression" is not used.

5.3 Longwall shearers

A study by the Bureau of Mines, by Cecala *et al*., published in 1994, sought to determine the optimal location for methane monitoring on longwall faces, noting that "It has been the Bureau's experience that in most mines the bulk of the methane on the face comes from the cutting of coal by the shearer" (p. 142). A full-scale model of a shearer and coal face was constructed where controlled methane releases could be monitored, recorded, and analyzed. Sufficient test runs were made for all investigated scenarios so as to be statistically significant when analyzed. Methane monitors were placed along the length of the shearer to determine dispersion characteristics of the methane-air mixture moving along the ventilated face. In addition to seeking an optimal sensor location, the researchers also considered the effect of water sprays on turbulence of the methane release. This latter analysis revealed, ". . . that water sprays created a substantial amount of turbulence and yielded higher concentrations of methane at the gas sampling locations on the top face side of the shearer machine than when no sprays were used" (p. 143). The significance of this is that the methane readings may be elevated by the presence of the water sprays, even though water sprays are seen as adding a significant contribution to overall safety at the cutting head.

Regarding the optimal location for the methane monitors on the longwall shearer, the authors conclude:

> The first choice for a machine-mounted monitor would be on the top face side of the shearer from at least 1.8m (6 ft) down from the headside cowl to the end of the machine.
>
> At those operations where coal and/or rock accumulations on the front part of the machine are a problem, a monitor near the gob side tail area should be considered. This location is less likely to be damaged by coal or rock, or negatively effected [*sic*] by water sprays. Walkway monitors do not appear to be very beneficial in quickly responding to high gas levels at the shearer. A methane monitoring system on the shearer should be viewed as a safeguard when engineering controls fail to keep gas levels at safe concentrations. (p. 144)

Nowhere in this article was there a discussion about de-energizing the shearer machine when methane was present, nor about the use of multiple monitors employing a voting scheme. However, it should be recognized, in viewing the last sentence quoted above, that the authors' perspective is commensurate with other research that has appeared in the literature, *viz*. the methane monitors are a safeguard when engineering controls, such as well-maintained water sprays and sharp cutter bits, begin to degrade.

6.0 Interaction of Methane and Coal Dust

Aim 5: To quantitatively assess the interactive effect of coal dust and methane in the event of an ignition.

The nuisance of coal dust as a source of explosions in underground coal mines and in coal preparation plants has been long established. The NFPA, aggregating data from the former U. S. Bureau of Mines and MSHA, estimates that methane ignitions outnumber methane explosions at a ratio of seven to one, and methane explosions outnumber coal dust explosions at a ratio of six to one. By extension, the ratio of methane ignitions to coal dust explosions (where methane is not present) is about 40 to 1. The concern with methane ignitions is the potential for a methane explosion which, in turn causes a shock wave through the underground mine which disperses coal dust and results in an explosion.

For a high-volatile bituminous coal dust dispersed in air, the lower explosive limit (LEL) is 0.05 oz. per cubic foot. As the NFPA Fire Protection Handbook notes, in its section on mining, “The presence of methane in the atmosphere increases the hazard by producing a linear reduction in the LEL for coal dust” (p. 8-176). Ever more stringent standards for rock dusting attempt to lessen the possibility of a methane explosion propagating a mine-wide coal dust explosion.

Cashdollar (1996) performed explosibility tests on both high-volatile bituminous coal, such as that from the Pittsburgh seam (which has been the standard for Bureau of Mines tests since the 1900s) as well as for low-volatile bituminous coals such as that from the Pocahontas seam. Particle size was also considered, with finer particles found to be more hazardous than larger particle sizes. As may be anticipated, for equal particle sizes, “more rock dust is required to inert the high-volatile Pittsburgh coal than is required for the low-volatile Pocahontas coal” (p. 74). In the presence of methane, the linear relationship of the explosibility of methane concentration and coal dust concentration, commonly referenced for the high-volatile bituminous coals of classic study, followed Le Chatelier’s Law for hydrocarbon gases. The slight non-linearity seen with the low-volatile Pocahontas coal was explained as, “This is probably due to the even greater difference in ignitability between the low-volatile coal and the CH_4, i.e. the dust becomes more easily ignited as more CH_4 is added. Therefore, the curvature is more likely an effect of ignitability rather than an effect of flammability” (pp. 73-74). Figure 4, reproduced from Cashdollar’s study, shows these ranges.

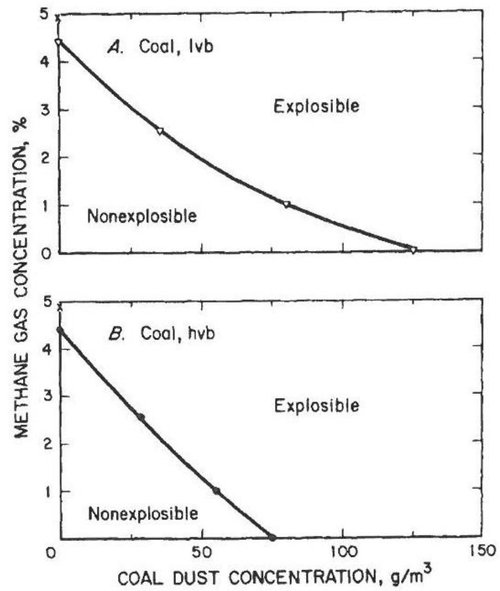

Figure 15 Minimum explosible concentrations of hybrid mixtures of coal dust and methane gas

Figure 4: Explosibility ranges for methane-coal dust mixtures, high- and low-vol bituminous coals [Cashdollar, K. L., "Coal Dust Explosibility, Cashdollar, *Journal of Loss Prevention for Process Industries*, Vol. 9, No. 1 (1996), p. 73].

Recognizing that most coal dust explosions are initiated by a methane ignition provides support for the position that reduction of methane ignitions should be of paramount importance to coal mine operators.

7.0 Discussion

Considering the classic "fire triangle," three conditions must be present for ignition of a methane-air mixture: fuel, oxygen, and heat sufficient to cause the ignition. Some methane will be emitted from the coal face, even if degasification has been performed prior to mining. Oxygen will be present since the face must be ventilated to provide for human occupancy. If a combustible mixture of methane and air exists at the working face, then a source of heat must be present to cause the ignition. Research has led to practical developments, such as degasification, that have limited the potential for methane at the working face. Dissipating that methane which is emitted from the working face is usually best controlled by proper ventilation, another topic that has received much investigation. The question of limiting methane ignitions at the face, then, revolves around eliminating, or reducing, sources of heat which are sufficient to cause ignition of a methane-air mixture.

Notable by its absence is the consideration of arcing by electrically powered mining equipment at the working face. Concentration is placed on the elimination, or reduction, of frictional ignitions, the largest contribution coming from worn bits and/or insufficient water sprays. Most frictional ignitions documented in MSHA field reports have been caused by metal bits cutting into sandstone, and to a lesser extent, pyritic material. Worn bits have also been a major, if not the major, contributing factor.

Automatic shutdown of permissible electrically powered face equipment provides safety for miners, then, not because of the removal of the potential for electrical arcing, but by arresting the cutting processes and limiting the possibility of frictional ignitions when a combustible mixture of methane-air is detected. The current generation of methane monitoring equipment is more robust, using better sensors and appropriate voting schemes, than that used in the past and, therefore, provides a better response than that anticipated in the late 1950s when regulations regarding equipment-mounted methane sensors were first implemented.

In considering the appropriate threshold value at which machine-mounted methane monitoring systems should automatically de-energize machinery, the focus should be placed on whatever perceived benefit such de-energization would have towards the goal of reducing frictional ignitions by eventual stoppage of the rotational motion of the cutter heads.

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