METHODS FOR CONTROLLING EXPLOSION RISK AT COAL MINE WORKING FACES

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ABSTRACT

At coal mine working faces, simultaneous application of three basic elements reduces the methane explosion hazard: (1) adequate ventilation, (2) regular monitoring of gas concentrations, and (3) the elimination of ignition sources. This paper reviews the application of these elements in a manner relevant to Chinese coal mines. Adequate ventilation is provided by using the mine entries to convey air for the long distances between the mine portal and the working sections (main ventilation systems) and then using line brattice or ventilation duct (face ventilation systems) to convey air the last hundred meters to the working face where coal is broken and removed. The air quantity provided is enough to safely dilute methane and the air velocity is enough to prevent layering.
Gas concentrations are regularly monitored in accordance with regulations using knowledge of the circumstances under which the highest concentrations are likely to be found. Ignition sources are eliminated by ensuring that electrical equipment does not ignite methane, that sparking from cutter picks is minimized, and that smoking by workers is strictly forbidden. Risk-reduction studies using fault-tree analysis have shown that large reductions in explosion risk only result from *multiple* preventive actions. For example, a ventilation upgrade or a methane monitor upgrade by itself offers risk reductions under 50 pct. A risk reduction of 90 pct. or more would typically require much more. Other studies have shown that the everyday vigilance of those working underground is as important as engineering design.

INTRODUCTION

Simultaneous application of three basic elements reduces the methane hazard at coal mine working faces:

- Large quantities of ventilation air circulated from mine portals to working sections through intake and return mine entries (main ventilation systems)and then to working faces using line brattice or ventilation duct (face ventilation systems).
- Regular monitoring of methane gas concentrations with gas detection instruments, along with subsequent action when a threshold level is attained.
- Elimination of ignition sources, including those that are worker-related.

The simultaneous application of several elements is necessary because in the event that one fails, the others continue to ensure safety. This paper discusses these three elements and shows how the methane hazard may be reduced in all types of coal mines. The list is not intended to cover every possible action to reduce the methane hazard. For details on other ways to reduce methane, see Kissell [2006] and the Code of Federal Regulations (see CFR in references).

PROVIDING ADEQUATE VENTILATION

Ample dilution to safe levels. Methane gas is explosive when mixed with air in the range between 5 and 15 volume % of gas. The 5 volume % value is the lower explosive limit (LEL). Methane concentrations in air that are below the LEL are not explosive. When methane is emitted from strata, it is usually at high concentration. As it progressively mixes with air, the concentration will pass through the explosive range and down below the LEL. A good ventilation system will supply enough fresh air to reduce all of the gas to far below the LEL as soon as the gas is emitted from the strata.

Main ventilation systems. Main ventilation systems circulate air from the portal to working sections of the mine. In the US, main ventilation systems in coal mines always employ the mine entries to move air, at least one entry for intake air and at least one entry for return air (Figure 1). Ductwork is never used in a main ventilation system. This reliance on intake and return mine entries rather than ductwork makes possible the movement of large air quantities over long distances necessary for methane dilution.

Face ventilation systems. Face ventilation systems carry air the last hundred meters to the working face where coal is broken and removed (Figure 1). In the US, either ductwork or line brattice is used for face ventilation. In most instances, the primary source of gas is at the working face, so it is vital to provide adequate ventilation air all the way to the face, that is, to the *last foot(30 cm)*. If, for example $100 m^3/s$ goes into the portal but only $1 m^3/s$ reaches the *last foot(30 cm)* at the working face where most methane is released, then as far as methane control at the working face is concerned, the mine is being ventilated with only $1 m^3/s$.

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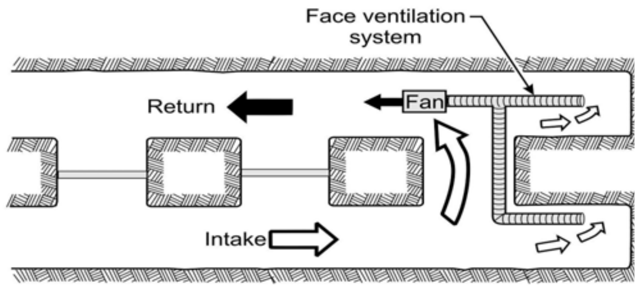

Figure 1. How main and face ventilation systems interact to bring large quantities of air to working faces. Main ventilation systems use mine entries (intake and return) while face ventilation systems use ventilation duct (illustrated) or line brattice. Black arrows represent contaminated air.

There are two categories of face ventilation: exhausting (Figure 2) and blowing (Figure 3). The exhausting system is the less efficient in clearing out methane gas from the face. For example, the face ventilation effectiveness[4] (FVE) of a 5-m^3/s airflow, 60-cm-diameter exhaust duct located 3m from the mine face is only about 0.10 [Wallhagen 1977]. In other words, the concentration of methane measured one foot (30 cm) from the face is 10 times higher than the concentration in the air passing through the duct.

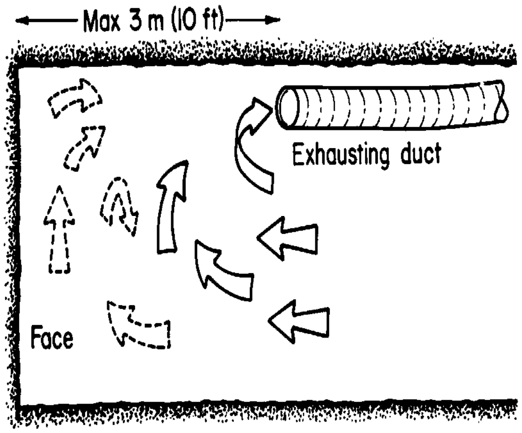

Figure 2. Exhausting system of face ventilation. Dotted arrows indicate a mixture of fresh air and contaminated air. For clarity, equipment is not shown.

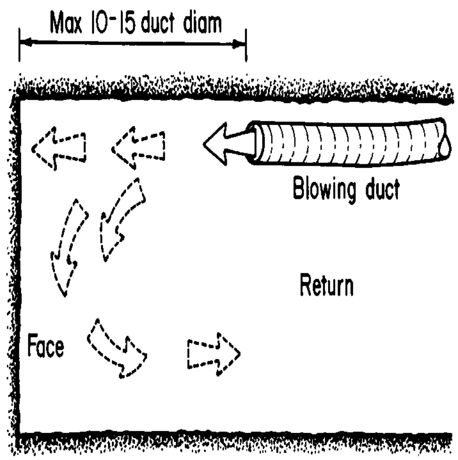

Figure 3. Blowing system of face ventilation. If the blowing duct diameter is 60 cm, the maximum distance from the face would be 6-9 m. Dotted arrows indicate a mixture of fresh air and contaminated air. For clarity, equipment is not shown.

If the end of the exhaust duct is more than 3 m from the face, the FVE is even less. Therefore, the end of an exhaust duct must always be 3 m or less from the mine face unless other means are used to ventilate the face, such as venturi air movers powered by compressed air.

Blowing face ventilation (Figure 3) is better for clearing out gas than exhaust ventilation because the momentum of the air in a blowing jet carries it farther. However, blowing systems also lose effectiveness as the face-to-duct distance increases. Therefore, the duct must be kept as close to the face as possible, with the end of the duct not more than 10–15 duct diameters from the face. The area must also be kept free of obstructions that would prevent the emerging jet of air from reaching the face.[5]

Studies of blowing ventilation at coal mine faces show that the FVE for a 5-m^3/s airflow, 60-cm-diam blowing duct at 6 m (10 duct diameters) is about 0.40, indicating that the concentration at the face is 2.5 times that in the return [Wallhagen 1977]. Thus, although 5 m^3 of air emerges from the duct per second, only 2 m^3 of air actually reaches the face. If the face emits 0.01 m^3 of gas per second, the average concentration in the immediate face area will be 0.01/2.0 or 0.5%, rather than 0.01/5.0 or 0.2%.

Whether exhausting or blowing ventilation is used, the end of the duct should be kept as close to the face as possible. If the face is drilled and blasted, keeping the ductwork in place is difficult. It is sometimes possible to move flexible ductwork forward and back on a trolley wire. Whatever method is used, when methane is present the

[5] The recirculation of contaminated air can be a problem with blowing face ventilation systems if the amount of fresh air delivered to the fan inlet is not adequate. See Figure 1-7 and the accompanying text in [Kissell 2006] for a discussion of recirculation.

need to keep the ventilation ductwork within the required face distance cannot be ignored, regardless of cost or inconvenience.

The importance of higher air velocity. Low air velocities can lead to poor mixing between methane and air. This poor mixing in turn leads to fluctuations in the methane concentration that make an ignition more likely.

Bakke et al. [1967] first suggested that a measurement of the methane concentration alone is an incomplete means of assessing the ignition hazard and that other measurable ventilation quantities might be important.[6] A study of methane ignitions in U.K. coal mines found that the probability of an ignition is determined by both the methane concentration and the densimetric Froude number, a dimensionless quantity related to the gas-mixing process in the presence of buoyancy forces. The expression for the Froude number F is

$$F = \frac{u^2}{g\frac{\Delta\rho}{\rho}\sqrt{A}}$$

where u is the air velocity, $\frac{\Delta\rho}{\rho}$ is the density difference between air and methane divided by the density of air, and A is the cross-sectional area of the airway.

The data available to Bakke et al. resulted from 123 ignitions on faces and gate roads at U.K. longwalls between 1958 and 1965. Examination of the data indicated that the risk of an ignition was dependent on more than methane concentration alone and that it was possible to combine concentration and Froude number in one variable of the form c^2/F. Figure 4 shows the normalized number of ignitions P (ignitions per year per gate road) versus c^2/F for the Bakke et al. data. The best fit to the data was $P = 0.004\ (c^2/F)^{0.9}$. A high correlation was obtained, indicating that, absent other sources of mixing, the risk of ignition P does depend on the variable c^2/F.

In most mines, $\sqrt{A}$ does not change much compared to changes in c^2 and u^2. Also, the factor of 0.9 in Figure 4 is close to 1.0. It follows that ignition risk varies with the quantity $(c/u)^2$. This departs from any notion that ignition risk depends on the concentration c alone.[7]

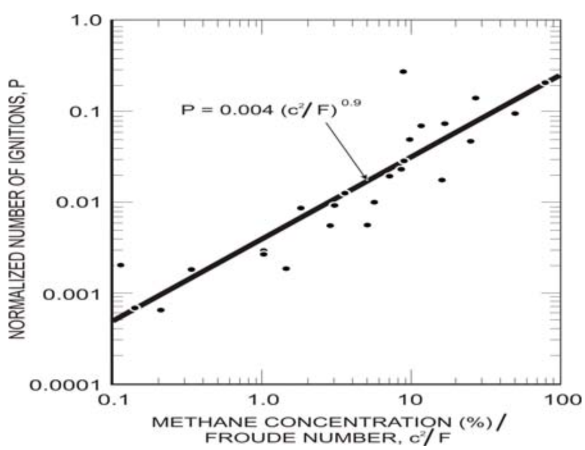

Figure 4. Ignitions per year per gate road.

As an example, assume that the methane concentration is 1.0% and that the air velocity is 0.5 m/s. If then the air velocity is raised to just 0.6 m/s, the methane concentration becomes 0.83%. If the ignition risk is proportional to $(c/u)^2$, this modest increase in air velocity cuts the ignition risk in half.[8]

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[6]Actually, since ignition risk also depends on human factors, there is no reason to expect that ignition risk depends only on concentration. Mines with less gas may also have a less vigilant workforce. However, Bakke et al. only sought a correlation with measurable ventilation quantities.
[7]Subsequent work at longwall shearers in the 1980s failed to confirm this finding [Creedy and Phillips 1997; CEC 1985], probably because water sprays on the shearer provided enough mixing between methane and air to overcome any velocity effect on mixing.
[8]Some confirmation of the importance of air velocity in reducing ignition risk was obtained by Bielicki and Kissell [1974], who conducted a study of the methane concentration fluctuations produced by incomplete mixing of methane and air at a model coal mine working face. Poor mixing was characterized by wider concentration fluctuations and resulted from low airflow or a high methane release rate. In other studies of methane-air mixing, Kissell et al. [1974] found that good mixing was characterized by normally distributed peaks and poor mixing by log-normally distributed peaks. Schroeder and Kissell [1983] found the same effect and suggested that the term σ(log c), the standard deviation of the logarithms of the sampled peak concentrations c, be used as an indicator of mixing.

The findings of Bakke et al. have important implications for using higher air velocity to prevent methane explosions:

- In the absence of other means to promote mixing, raising air velocity is a highly effective way to reduce ignition risk. Higher air velocity promotes better mixing in addition to lowering the average concentration.
- High pressure (>10 bar) water sprays and auxiliary air movers (small fans or compressed-air venturis) that promote mixing can reduce ignition risk.
- At similar methane concentration levels, tunnels or mines with large cross-sectional entries and low air velocities have higher risk of ignition than those with small cross-sectional entries and higher air velocities. Both the lower velocity and higher area will work together and result in a lower Froude number.

LAYERING OF METHANE AT THE MINE ROOF

The density of methane is roughly half that of air, so methane released at the mine roof may form a buoyant layer that does not readily mix into the ventilation air stream. Such layers have been the source of many mine explosions,[9] so it is important to understand the circumstances that lead to the formation of methane roof layers and the methods used to dissipate them[10].

Detecting methane layers. The formation of methane layers is largely a result of inadequate ventilation. Raine [1960] asserted that a measurement of ventilation velocity is of most practical importance. He found that under conditions of "normal firedamp emission,"[11] an air velocity of 0.5 m/s measured at the roof was enough to prevent layering.[12] Most current-day estimates of the necessary velocity are close to this value.[13] Aside from inadequate ventilation, there are other circumstances under which methane layers are probable. Airways next to gobs are an example. Many of the concerns about layers were sharpened by experience in the 1960s with advancing longwalls in the United Kingdom. At these longwalls, frequently traveled gate roads were directly adjacent to fresh longwall gob, where broken overburden provided a ready pathway for roof gas emissions.

Thorough gas monitoring is a key to dealing safely with methane layers. Care in monitoring is particularly important under the following conditions:

- The air velocity measured at the roof level is 0.5 m/s or less.
- The airway is next to a gob[14] or intersects a geologic anomaly, such as a fault, that can serve as a conduit for gas.
- The mine roof (or tunnel crown) is not within easy reach, so measurements at roof level are less apt to be carried out regularly.
- The airway has cavities [Titman et al. 1965; Vinson et al. 1978] or roof-level obstructions to air movement.
- The airway is inclined more than 5°. Airways inclined 20 to 30 degrees require 50% greater ventilation velocity if the air moves uphill [Bakke and Leach 1962].

Workers who test for methane layers should be aware that the gas concentrations in these layers may fall outside of the accurate operating range of catalytic heat of combustion sensors. For accurate operation of these sensors, in most cases the concentration of methane must be below 8% *and* the concentration of oxygen must be above 10%.

Mitigating methane layers. Methane layers are removed by increasing the ventilation velocity and reducing the gas flow by methane drainage. In instances where the methane source and layer size are limited, a less satisfactory but workable method is to use a (well-grounded) compressed air-powered venturi air mover or an auxiliary fan at each methane source to blow air at the source of the layer and disperse it [Creedy and Phillips 1997]. In either case, an aggressive sampling program is necessary to ensure safe conditions[15].

The rib and floor as sources of methane layers. Methane layering occurs when methane is released at the mine roof. When methane is released at the mine floor or rib, this gas readily mixes into the ventilation air stream, losing its buoyancy. Figure 5, from Bakke and Leach [1962], compares 2-cfm (1 l/s) methane sources at the roof, rib, and floor of the mine entry. Only the roof source produced a significant methane layer at the 2-cfm (1 l/s) rate.[16]

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[9]For example, the 1993 Middelbult coal mine explosion in Secunda, South Africa, was attributed to a methane layer [Davies et al. 2000].
[10] Creedy and Phillips [1997] have written a thorough summary of methane layering and its implications for South African mines.
[11]The phrase "normal firedamp emission" was not further defined. However, it is clear that at abnormally high gas feeds, higher velocities are required. In a laboratory study, Bakke and Leach [1962] found that 1.2 m/s air velocity was required to disperse a layer generated by a release of $0.34 m^3$/min of methane.
[12]The 0.5 m/s applies only to horizontal entries. Higher velocities are suggested for inclined entries [Bakke and Leach 1965].
[13]For example, McPherson [2002] suggests 0.4 m/sec, or about 80 ft/min.
[14]Five miners were killed in a 1972 methane explosion at the Itmann No. 3 Mine in West Virginia. The explosion was in a trolley haulageway that ran adjacent to a longwall gob and was attributed to excessive pressure from the adjacent strata [Richmond et al. 1983].
[15] Keep in mind that methane mixed with air cannot unmix to form a layer.
[16]The testing did not rule out the possibility of a layer at higher methane flows.

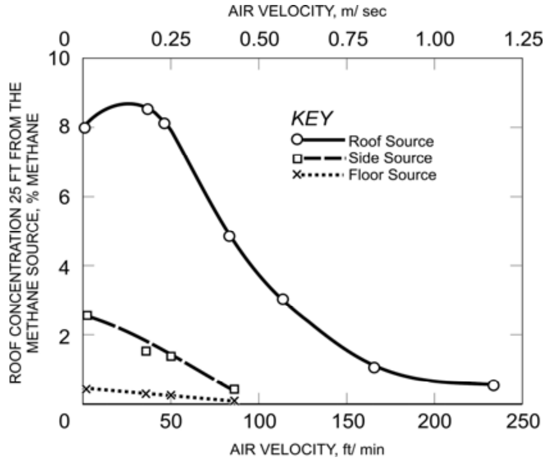

Figure 5. Methane layering with roof, side, and floor sources (from Bakke and Leach [1962]).

USING PORTABLE METHANE DETECTORS

Taking a gas reading with a portable methane detector is a simple matter. Where to measure and how to interpret the reading requires more expertise.

Methane measurements. Most methane measurements[17] should be made as follows:

- Close to the methane source, where higher concentrations are more likely to be encountered.
- Close to the mine roof, where higher concentrations are more likely to be encountered.
- Where roof falls have created cavities in the top that may be ignored during routine checks.
- In regions where the dilution of methane is impaired, i.e., those that are poorly ventilated and those where air movement is blocked by equipment.
- While cutting is underway, because the methane release rate is higher as coal or rock is broken and the mining machinery advances.
- On the side of the entry that normally sees the highest concentrations. For exhaust ventilation systems, this is normally the same side of the entry where the exhaust duct (or curtain) is located. For blowing ventilation, it is normally the opposite side of the entry from the blowing duct (or curtain).
- On mining machinery. In mines using continuous miners or longwall shearers, an additional methane detector is mounted on the equipment and wired to shut down the machinery if a threshold concentration is exceeded.

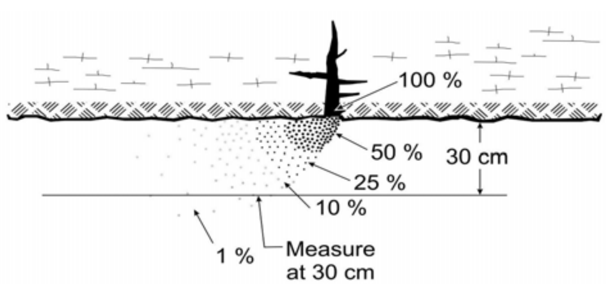

Figure 6. Depiction of methane being diluted into a moving air stream.

In making measurements, consideration must always be given to how methane is released and diluted to safe levels. Methane entering a mine or tunnel often enters as a localized source at high concentration. An example is shown in Figure 6, which depicts a cloud of methane being diluted into a moving air stream. As shown in the figure, methane enters through a crack in the coal. If no air enters the crack, the methane concentration in the crack can be close to 100%. However, as the methane emerges from the crack, it progressively mixes with and is diluted by the ventilation air. Suppose this progressive dilution reduces the concentration from 100% to 1%, as shown in Figure 6. In this case, the instrument reading depends highly on the location of the measurement— a critical concern if one

[17] For portable methane detectors, the required sampling time interval in the US is a gas check every 20 min. Methane detectors on mining machinery operate continuously.

intends to use the reading to assess whether a hazard exists. This problem is handled by requiring methane measurements at a distance of not less than 30 cm from the roof, face, ribs, and floor. If there is enough gas coming from the crack (or other source) to exceed statutory limits at a 30-cm distance, then a hazardous condition exists.

If a methane layer is likely, measurements must be taken at distances less than 30 cm because the thickness of such layers can be less than 30 cm. The degree of hazard resulting from a high-concentration layer of gas must be assessed from measurements of the size of the layer as well as the location and size of the source.

Misinterpreting warning signs. It is not unusual to misinterpret a gas warning sign, especially in underground workings thought to have no gas. A primary reason is that the gas flow varies with the excavation rate. Suppose, for example, that a mining machine begins to cut into an area of gassy ground, releasing methane into the ventilation air. The machine-mounted monitor on the mining machine senses this gas and shuts the machine down. After tracking down the source of the shutdown, a worker begins to hunt for gas with a handheld detector, but the worker hunting for gas cannot detect much gas because the emission dropped when the machine stopped. Thus, everyone concludes that the monitor on the machine is not working properly. Given two instruments, one with bad news and the other with good news, the tendency is to believe the good news. However, when methane detection and monitoring instruments fail, they rarely give a false alarm or a false high reading; in other words, they rarely indicate gas when there is none. The usual failure mode is to not register gas that is present. Therefore, when any instrument registers gas, it is better to trust the reading and take appropriate precautions.

Operators must be especially cautious when successive methane readings vary more than they normally should. When the airflow is low or when measurements are taken close to the source of the gas, the methane will not be well mixed into the air. This could lead to a high reading in one area with a low reading just a few feet away. This incomplete mixing can indicate that the ventilation air is deficient and that even higher concentrations of gas might be found nearby.

The bump test. It is a good idea to perform a quick "bump test" on every portable methane detector to ensure that it is working properly. Before every shift, briefly expose the portable detector to a known concentration of methane gas high enough to set off the methane alarm. Note the reading to ensure that it is correct. A bump test is not a calibration, but a quick way to ensure that the most important functions of the instrument are intact.[18]

Person-wearable methane monitors. Person-wearable methane monitors are a new development in gas monitoring. These are lower-cost (typically around $400), light- weight devices that operate continuously to warn miners of any gas accumulations. An example is the Iyoni II methanometer, integrated into a miner's cap lamp (Figure 7). The light blinks when methane is encountered.[19] Other person-wearable methane monitors are also available. Typically, these have visual, audible, and vibratory alarms that produce signals to warn the user when a preset methane level is exceeded. NIOSH recently evaluated seven of these, finding that several had a satisfactory battery life, accuracy, response time, and alarm intensity [Chilton et al.2005].

Figure 7. The Iyoni II methanometer is incorporated into a cap lamp

REDUCING IGNITION SOURCES

Up to this point, the emphasis has been solely on ventilation methods and monitoring for gas. However, the chance of a methane ignition may be further reduced by dealing directly with the ignition source. One obvious ignition source is faulty electrical equipment that has not been designed or maintained for ignition prevention. The other ignition source results from cutter bits striking rock. In this instance, abrasion from the rock grinds down the rubbing

[18] A similar test is described by the Canadian Standards Association [CSA 1984].
[19] The Iyoni II has been evaluated by NIOSH [Chilton et al. 2003].

surface of the bit, producing a glowing hot metal streak on the rock surface behind the bit. The metal streak is often hot enough to ignite methane, causing a so-called frictional ignition. In the US, frictional ignitions are much more prevalent than those from faulty equipment.

Bit changes to reduce frictional ignitions. The most important action one can take to reduce frictional ignitions is to replace bits regularly, thus avoiding the formation of wear flats on the bits. Frictional ignition with a mining bit always involves a worn bit having a wear flat on the tip of the bit [Courtney 1990]. A small wear flat forms a small hot spot, which does not lead to an ignition, whereas a large wear flat forms a large hot spot that is more likely to cause an ignition. Also, mining bits consist of a steel shank with a tungsten carbide tip. The steel is more incendiary than the tungsten carbide tip, so if the tip is worn off and the steel shank exposed, the chance of an ignition is much greater. As an example, Figure 8 shows the results of a test in which a cutter bit was used to cut a sandstone block in the presence of an ignitable methane concentration. With the tungsten carbide tip in place, no ignitions were obtained even after 200 or more cuts. With the steel shank exposed, ignitions quickly began. With as little as 3 mm bit wear, fewer than 10 cuts were necessary to produce an ignition.

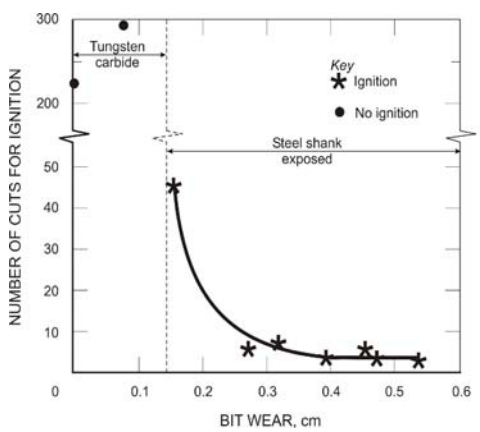

Figure 8. Effect of bit wear on frictional ignition [Courtney 1990].

Other methods to reduce frictional ignitions are to change the attack angle and tip angle of conical bits [Courtney 1990] and to use radial bits instead of conical bits [Phillips 1996]. McNider et al. [1987] reported a decrease in frictional ignitions by using bits with larger carbide tips and by changing the bit attack angle.[20]

THE IMPORTANCE OF HUMAN FACTORS AND MULTIPLE PREVENTIVE ACTIONS

The importance of human factors and multiple preventive actions in reducing methane explosion risk was identified in a study by Kissell and Goodman [1991]. Using a risk assessment technique, fault tree analysis, the authors examined the possible causes of tunnel methane explosions. The intent was to provide a relative ranking of the events or combinations of events most likely to contribute to an explosion.

Human factors. In the Kissell and Goodman study, 15 "initiating events" were identified to represent starting conditions that can lead to an explosion (Table 1). As evidenced in Table 1, most initiating events involve a human factor rather than an engineering specification. Therefore, safe conditions require the everyday vigilance of those working underground. This does not undermine the importance of good engineering design, it only emphasizes that the job of providing safe conditions just begins with design. For example, workers must maintain overlap in auxiliary systems as mining advances, regularly check the ventilation quantity and methane concentration, and adequately service the methane monitors. Equally important, workers must not smoke underground; those who do risk causing an explosion if methane is present.

Multiple preventive actions. Another conclusion from the fault tree study was that large reductions (over 90%) in the risk of an explosion only result from *multiple* preventive actions. For example, a ventilation upgrade or a methane monitor upgrade by itself offers risk reductions under 50%. A risk reduction of 90% or more would typically require both of these, plus additional actions such as more thorough gas checks during welding.

[20]Changing the bit attack angle can also raise the cutting force, requiring a change in drum design.

Table 1.—Initiating events for tunnel methane explosions
(from Kissell and Goodman [1991])

Human factors primarily involved:
1. Ventilation duct setback from face is too great
2. Use of a scavenger system with inadequate overlap
3. A fan is turned off
4. Fan performance is seriously degraded
5. Ductwork has serious leaks
6. Ductwork is seriously pinched
7. Smoking or welding occurs
8. Methane monitor calibration is off
9. Equipment used is not explosion-proof operationally
10. Gas checks are not made before or during welding

Combination of human factors and engineering specifications:
1. Methane monitor disabled or not present
2. No other warnings of excess gas are provided

Engineering specifications primarily involved:
1. Ductwork is seriously undersized
2. Equipment not explosion-proof by design

Neither engineering or human factors involved:
1. Cutter pick sparking

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