CHAPTER 14.—PREVENTING METHANE GAS EXPLOSIONS DURING TUNNEL CONSTRUCTION

By Fred N. Kissell, Ph.D.[1]

In This Chapter

- ✓ Early indicators of a gas problem
- ✓ How the methane hazard is reduced
- ✓ Ventilation principles for gassy tunnels
- ✓ Monitoring for gas
- ✓ Eliminating ignition sources

and

- ✓ The all-important human factors component

This chapter gives guidelines for preventing methane gas explosions during tunnel construction. Emphasis is placed on assessing the hazard potential, on ventilation principles, and on monitoring for gas.

The chapter also emphasizes the importance of human factors in reducing explosion risk. Ensuring safe conditions is much more than just good engineering design. It also involves the everyday vigilance of those working underground. This does not imply that the engineering design can be ignored, only that the job of providing safe conditions has just begun with design.

EARLY INDICATORS OF A GAS PROBLEM

For the engineer planning a tunnel project, reliable early indicators of methane are scarce. However, the local geology can often provide some information.[2] Carbonaceous rocks and tar sands are a likely methane source. Gas is also a distinct possibility if it is known to be present elsewhere in the same sequence of geologic formations. Swampy areas, sewerage systems, and landfills are also candidates because the decomposition of organic materials produces methane. The gas in a tunnel can originate in the strata being excavated, or it can migrate a considerable distance from adjacent strata.

Test borings at the project site can also serve as initial indicators of gas. Methane has no odor, but may be emitted along with gases that do. If gas is emitted from the borehole, a sample may be collected by inserting a tube into the hole as far as possible and pumping the gas out. The gas sample should be collected in a sampling bag or canister for later analysis by a chemical laboratory.[3]

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[2]A good source of information on hazardous ground gases is Doyle [2001].

[3]Most handheld methane detectors require the presence of 10% oxygen in the sample to operate properly, and this much oxygen is not normally found in borehole samples. For more information on methane detection, see the sampling chapter (Chapter 2).

Gas flowing from just one test boring indicates a potentially larger gas problem. Immediate measures must be taken to confirm the presence of methane by laboratory analysis and to sample all of the other boreholes that are part of the project. In addition to testing for methane, laboratory analysis should also test for other gases that may be flammable or toxic, such as ethane or hydrogen sulfide.

INDICATORS OF GAS UNDERGROUND

In tunneling and hard-rock mining, methane is not normally encountered. Therefore, the mistaken inclination is to not suspect the presence of gas.

There have been many methane explosions in places where the existence of gas was never suspected or was thought to be minimal. A basic problem is that the commonly used catalytic detectors are not very good at detecting very low concentrations of gas. Figure 14–1 illustrates a representative situation (the ventilation quantities in the figures are only provided as examples). In this figure, the main tunnel fan moves air at a rate of 10,000 cfm and the scavenger fan moves air at 5,000 cfm. Methane gas enters the tunnel at the face at a rate of 1 cfm. First, the gas concentration is measured in the main fan line. With 1 cfm of methane in 10,000 cfm of air, the concentration will be 1/10,000, or 0.01%. Next, the methane concentration in air returning from the scavenger fan duct is measured; here, the concentration is 1/5,000 or 0.02%. With most commonly used catalytic detectors, these low percentages will show up as zero. However, even if methane were detected, such low concentrations would usually be considered negligible.

Is this level of gas hazardous? Obviously not under the conditions in which the measurements were made. However, consider the following scenario. The 5,000-cfm scavenger ventilation goes off for 10 min because of an electrical problem. Ten cubic feet of methane then accumulates in the face area. This quickly dilutes to 100 ft^3 of a 10% methane explosive mixture, and thus an explosion occurs in a tunnel where no one had initially measured any gas.

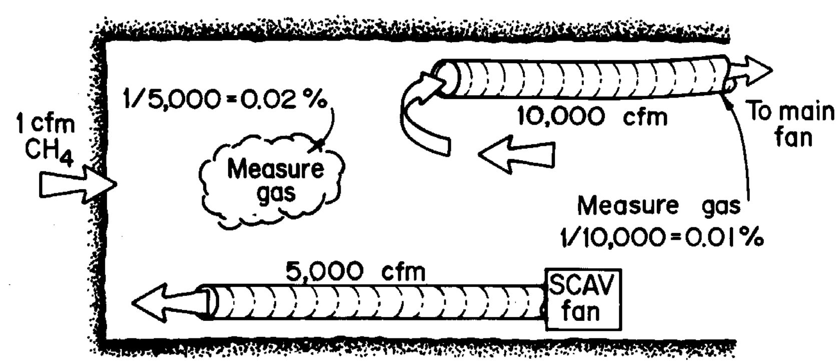

Figure 14–1.—Low concentrations of methane gas.

This might sound far-fetched, but many workers have died under very similar circumstances. Gas checks had been made when the ventilation system was working well. Later, the ventilation failed for some reason, and lethal quantities of gas accumulated, causing an explosion.

Ways to confirm the presence of gas underground. Given that low emissions of methane can be hazardous, how does one determine if there is a potential methane problem, assuming that there were no clues from exploration boreholes? There are three possible ways.

1. Look for gas in the parts-per-million range. When testing for methane gas, return air samples should be collected in a bag or bottle specially designed for gas sampling. A laboratory analysis that uses a chromatograph to look for gas in the parts-per-million range is then conducted. Applying this method to the scenario in Figure 14–1, the return air sample would have shown 100 ppm, a definite indicator of gas in low quantities.[4] When sampling, the ambient air on the surface should also be measured, as it generally contains a few parts per million of methane.

2. Hunt for gas when ventilation is temporarily off. It is common for tunnel ventilation systems to be down for short periods while fan changes are being made or ductwork extended. Because even low gas emissions accumulate to measurable levels quickly, this is an opportune time to hunt for gas accumulations with a handheld methane detector. If gas has already been shown to exist, this hunt is an important safety measure.

3. Look for gas in those places where it is most likely to accumulate. Gas emitted at the face will accumulate in unventilated corners near the face. Emissions from small cracks or fissures near the crown may produce a methane layer there because methane is much lighter than air. In operations using a tunnel boring machine (TBM), gas accumulations near the muck discharge point are likely. If the tunnel is unlined, any location along the entire length is a potential site for a methane layer at the crown.

As with surface samples, the initial presence of gas underground must be confirmed to a higher level of accuracy by laboratory analysis. If a field instrument shows that gas is present, an air sample must be collected in a bag or bottle specifically designed for gas sampling. The analysis is normally conducted with a carefully calibrated gas chromatograph. To be effective, the hunt for gas in tunnels must be conducted at frequent intervals. This is the only way to detect gas in isolated pockets. If the presence of gas is suspected but not yet confirmed, the tunnel air should be tested for methane with a handheld instrument at least twice per shift.

PROVIDING ADEQUATE VENTILATION

Ample dilution to safe levels. Enough ventilation air must be provided to immediately dilute the methane gas to safe levels as soon as the gas enters the tunnel. Methane is combustible when mixed with air in the range between 5 and 15 vol % of gas. The 5 vol % value is the lower explosive limit (LEL). Methane concentrations in air that are below the LEL are not explosive. The 15 vol % value is the upper explosive limit. Gas mixtures with concentrations above this limit are not explosive, but may become so if mixed with more air.

[4]Low levels of methane gas have been found in a wide variety of hard-rock and noncoal mines. For mines classified as gassy by the Mine Safety and Health Administration, Thimons et al. [1979] found that the return air methane concentrations were 70 ppm or higher. No similar research on methane has been conducted in tunnels, but there is little doubt that a comparable value in a return airflow of 10,000 cfm would show hazardous quantities of gas.

Simultaneous application of three basic elements reduces the methane hazard:

- **Adequate ventilation.**
- **Regular monitoring of air quantities and gas concentrations, with automatic equipment shutoff at high gas concentrations.**
- **Elimination of ignition sources, including those that are worker-related.**

The simultaneous application of several elements is necessary because if one fails, the others continue to ensure safety.

When methane is emitted from the 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.

In referring to gas concentrations, different government agencies may use different terminology. For example, in regulating coal mines, the Mine Safety and Health Administration (MSHA) specifies that the concentrations of methane at coal mine working faces remain below 1.0 vol %. This is the same as 20% of the LEL. With the LEL of methane in air at 5 vol %, 20% of 5 vol % is 1.0 vol %. Specifying a percentage of the LEL is advantageous when mixtures of flammable gases are emitted.

Main ventilation systems. Main ventilation systems carry air from the portal into the TBM trailing gear. These are classified as either blowing or exhausting. In blowing systems, fans located on the surface and along the ductwork push air through the ductwork into the tunnel. In exhaust systems, air in the ductwork flows out of the tunnel. Each system has its advantages. Selection of either an exhaust or a blowing main ventilation system will depend on whether a face shield and scrubber are used, on whether or not a scavenger system is used, and on the type of ductwork used.[5]

Face ventilation systems. Face ventilation systems carry air from the trailing gear to the face of the tunnel where rock is broken and removed. In most instances, the primary source of gas is at the face, so it is vital to provide adequate ventilation air all the way to the face, that is, to the *last foot.*[6] For this reason, the ventilation focus of this chapter is on face ventilation.

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[5]When planning a tunnel ventilation system, make a simple diagram of all ductwork and airflow movement to ensure that the ventilation mistakes described in this section are not incorporated into your plans.

[6]In some instances it is also necessary to focus attention on the muck discharge point. For example, in earth pressure balance machines most of the methane may be released at the end of the screw conveyor. A nearby fan or compressed air venturi can be used to dilute this gas, but does not relieve the need to provide adequate ventilation all the way to the *last foot.*

The tunnel face is usually ventilated with much less air than you think. If 20,000 cfm goes down the shaft but only 2,000 cfm reaches the face, then as far as methane control is concerned the tunnel is being ventilated with only 2,000 cfm.

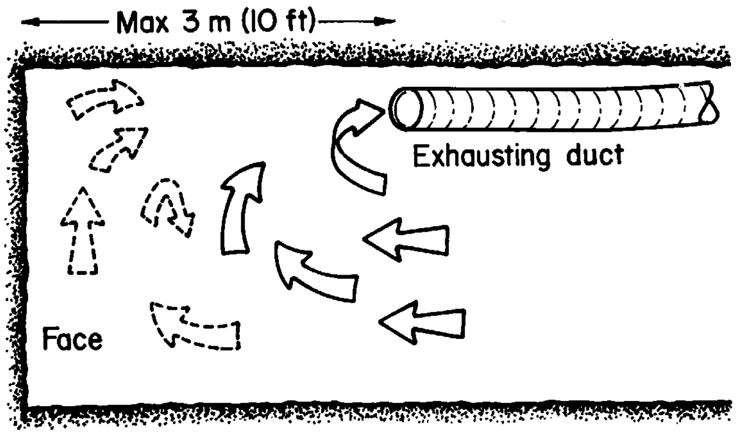

Figure 14–2.—Exhausting system of face ventilation. For clarity, the equipment is not shown.

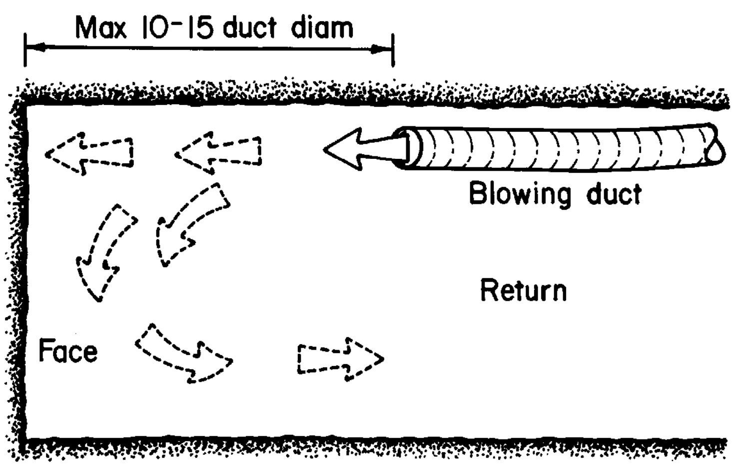

Figure 14–3.—Blowing system of face ventilation. If the blowing duct diameter is 2 ft, the maximum distance from the face would be 20–30 ft.

There are two categories of face ventilation: exhausting (Figure 14–2) and blowing (Figure 14–3). The exhausting system is the less efficient in clearing out gas from the face. For example, the face ventilation effectiveness[7] (FVE) of a 10,000-cfm, 24-in-diam exhaust duct located 10 ft from a mine face is only about 0.10. In other words, the concentration of methane measured near the face is 10 times higher than the concentration in the air passing through the duct [Wallhagen 1977]. If the end of the exhaust duct is more than 10 ft from the face, the FVE is even less. Therefore, the end of an exhaust duct must always be 10 ft or less from the tunnel face unless other means are used to ventilate the face, such as venturi air movers powered by compressed air.

Blowing face ventilation (Figure 14–3) 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. The duct must be kept as close to the face as possible, with the end of the

[7]FVE is an indicator of the proportion of air reaching the last foot, i.e., a distance of 1 ft from the face.

duct not more than 10–15 duct diameters from the face. There also must be no obstructions that would prevent the emerging jet of air from reaching the face.

Studies of blowing ventilation at coal mine faces show that the FVE for a 10,000-cfm, 24-in-diam blowing duct at 20 ft (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 10,000 ft^3 of air emerges from the duct per minute, only 4,000 ft^3 of air actually reaches the face. If the face emits 20 ft^3 of gas per minute, the average concentration in the immediate face area will be 20/4,000 or 0.5%, rather than 20/10,000 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 particularly difficult. Blast shields can help, but may hinder clearing the face. It is sometimes possible to move flexible ductwork forward and back on a trolley wire. Another possibility is inflatable cloth ductwork, which is inexpensive and may be considered expendable. Whatever method is used, when methane is present the need to keep the ventilation ductwork within the required face distance cannot be ignored, regardless of cost or inconvenience.

Which face ventilation system is best? In principle, blowing ventilation systems provide better dilution of methane at the face, but it does not always follow that it is better to use blowing face ventilation in a tunnel. For example, Figure 14–4 illustrates the face ventilation of a small-diameter TBM with an enclosed cutter head. In this example, 5,000 cfm is withdrawn from the cutter head enclosure through duct #1. An airflow above 5,000 cfm would be better, but there is not space for larger ductwork at the front of the TBM. So, an additional 5,000 cfm is provided with a second ventilation duct (duct #2) that extends to the front of the trailing gear and blows air toward the face.

The problem with this system is that it has equal duct airflows moving in opposite directions, leading to a stagnant zone of low airflow (see Figure 14–4) where methane may accumulate. Also, it only delivers 5,000 cfm to the face, even with the two ducts. To avoid zones of low airflow, ventilation designs that move air through ductwork in opposite directions should be avoided. To demonstrate, if ventilation duct #2 exhausted air from the face instead of blowing toward it (as shown in Figure 14–5), then the front of the tunnel would be ventilated with 10,000 cfm of air instead of 5,000 cfm, and there would be no zone of low air movement.

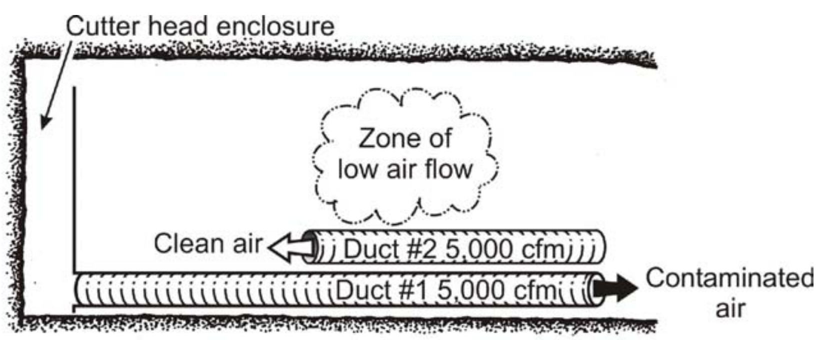

Figure 14–4.—TBM ventilation system with low airflow zone where methane dilution suffers.

In this example, venturi air movers powered by compressed air are used for additional air movement in the space between the end of duct #2 and the cutter head enclosure.

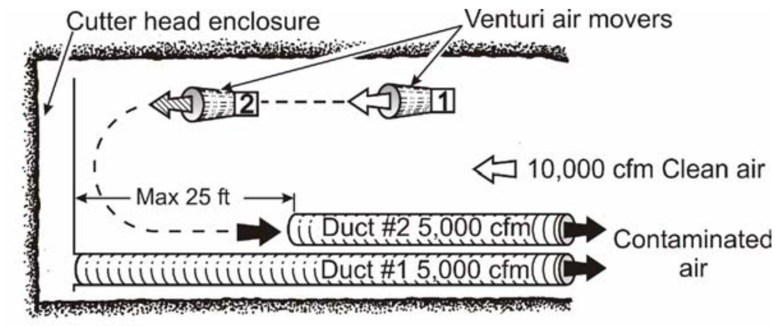

Figure 14–5.—TBM ventilation system with second duct exhausting air from the face. Venturi air movers provide additional air movement.

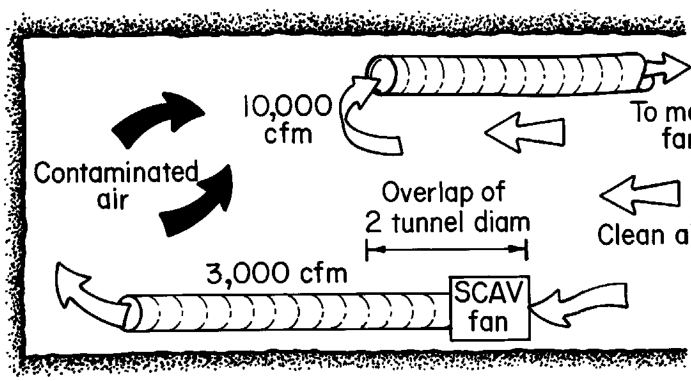

Figure 14–6.—Auxiliary system with adequate overlap (not to scale).

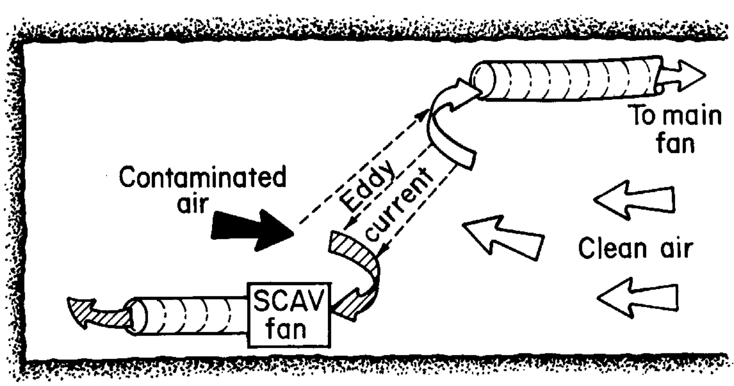

Figure 14–7.—Auxiliary system with no overlap and poor methane dilution.

Auxiliary face ventilation systems. A common way to ventilate the tunnel face is to use an auxiliary ventilation system (Figure 14–6). Auxiliary face ventilation systems ventilate the tunnel face with a fan and duct that are separate from the main ventilation system. Auxiliary systems are often called scavenger fans.

A critical feature of auxiliary systems is the required overlap with the main ventilation duct, since auxiliary systems that do not overlap properly suffer huge efficiency losses. Figure 14–6 shows a simple two-duct auxiliary system that is working properly. The main duct is on exhaust, with the fan on the surface; the scavenger, or auxiliary fan, is blowing toward the face. Note that the inlet of the scavenger fan is in the fresh air stream of the main ventilation duct. Figure 14–7 shows the same arrangement, but with no overlap. The inlet of the scavenger fan picks up contaminated air returning from the face rather than fresh air, creating recirculation. Eddy currents between the two inlets provide the only air to the face, greatly reducing the amount of fresh air available to dilute methane. To prevent this scenario, the two ducts must overlap by at least twice the tunnel diameter (Figure 14–6).

Unfortunately, overlap is not something that can be engineered into the system from the start. New sections of fan line must be promptly added as the tunnel advances. Adequate overlap is maintained only through continued around-the-clock vigilance of the tunnel crew. For this reason, it is a major problem area.

With auxiliary systems, ventilation efficiency also suffers when airflow directions are not coordinated. Figure 14–8 depicts a scenario in which the airflow directions are not coordinated. Figure 14–8 is similar to Figure 14–6 except that the main duct is now blowing. The scavenger fan inlet is now in the contaminated return air, and contaminants are recirculated back to the face. The impact is that the fresh air reaching the face is reduced by up to one-half. Whatever the arrangement of ducts and fans, workers must check carefully to be sure that fresh air is not being replaced by recirculated air (see footnote 5).

A scavenger fan with inadequate overlap can recirculate 90% of the air returning from the face. In such an instance, a 3,000-cfm scavenger fan will deliver only 10% or 300 cfm of fresh air to the face.

Minimizing leakage. Leakage in both main and face ventilation systems is another source of airflow losses. Factors that impact leakage are fan placement, ductwork diameter and length, pressure drop, and duct condition. It is not unusual to lose half of the airflow in a long run of ductwork. In planning, the largest practical diameter of duct should be used. Damaged ductwork should never be installed, particularly if the ends are buckled.

Another major source of leakage (and recirculation) is the "trombone" section in the trailing gear, where concentric ventilation ducts slide apart and new sections of duct are added as the trailing gear moves forward. Recirculation of contaminated air can be particularly high as new sections of ductwork are added. This leakage and recirculation may be minimized by locating fans on both sides of the trombone section and balancing the fan flows to minimize the pressure drop between the air passing through the trombone and the outside tunnel air.

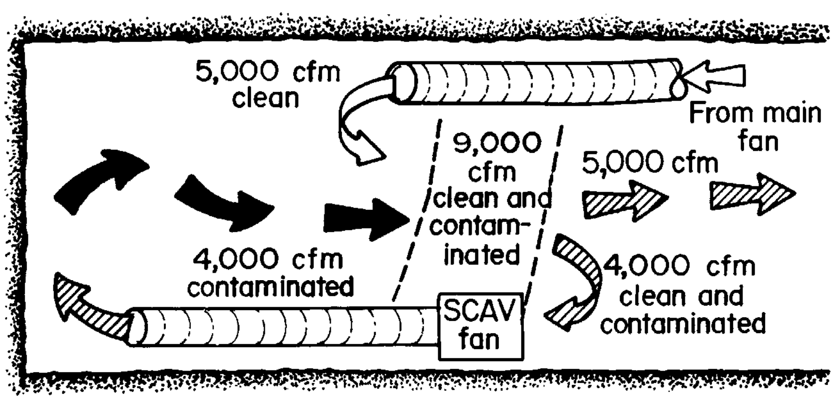

Figure 14–8.—Loss of efficiency from mismatched airflow directions.

Cumulative ventilation inefficiencies. Cumulative ventilation inefficiencies include leakage in the main duct, leakage at the trombone connection, auxiliary system problems, and low face ventilation effectiveness because the end of the ductwork is too far from the face. While one of these elements alone may not be significant, the cumulative effect of several will certainly be.

Venturi air movers. Compressed air is ineffective as a primary fresh air source because it cannot deliver enough air for adequate dilution of gas. However, there are some circumstances where compressed air can serve as an adjunct to conventional ventilation, particularly to enhance the air velocity over short distances. For example, if an exhaust ventilation system is being used, a venturi-type air mover powered by compressed air can provide better dilution of methane at the face, *provided* that the air mover is located in fresh air.[8]

A good way to align venturi air movers is shown in Figure 14–5. Here the air movers are placed on the opposite side from the exhaust duct so as to generate a U-shaped airflow pattern that feeds contaminated air to the duct inlet. Note in Figure 14–5 that venturi #1 is outby the inlet of duct #2 and is in the 10,000-cfm fresh air stream produced by both ducts #1 and #2. Also, venturi #2 is placed directly forward of venturi #1.

Venturi systems will recirculate a high proportion of the airflow, and the amount of recirculation will grow as the distance and the number of venturis grow. As a result, a venturi system is not effective for distances over 25 ft, as indicated in Figure 14–5.

Checking the ventilation system. To adequately check the ventilation system, a regular program of airflow measurements must be used, with airflows measured at least weekly. Airflow in all ducts must be measured, along with the airflow in the center line of the tunnel. Even if there are no leaks, it is common for ductwork to be clogged with muck.

Tunnel workers should always be on the lookout for ventilation danger signals. Does ventilation duct always extend throughout the tunnel and close to the face? Is there always an adequate overlap? Is the ductwork sealed against leaks? Are the fans always running? Unless the tunnel has a diameter of 20 ft or more, is there obvious air movement everywhere in the tunnel? Is the air unusually warm or dusty?

MONITORING FOR METHANE

If methane is found, either at boreholes or during tunnel construction, regular monitoring must be scheduled. The most likely place to find methane is in the face area of the tunnel.[9] Gases emitted at the face will collect there in unventilated corners. Emission from feeders or faults near the crown may produce a methane layer there, particularly in unlined tunnels. On faces that are drilled and blasted, workers must check for methane before blasting. If a TBM is being used,

[8]Venturi air movers must be grounded to prevent the buildup of static electricity.
[9]There may be exceptions. See footnote 6.

methane can accumulate at the muck discharge and behind the face shield. Finally, workers should also check for gas before and during welding and cutting operations.

In tunnels known to have methane, preshift and midshift gas checks are minimum requirements. The frequency of other checks depend on whether continuous detectors are also present, the extent of the hazard, and the applicable regulations. The Occupational Safety and Health Administration (OSHA) safety and health standards for underground construction [29 CFR[10] 1926.800] require continuous monitoring when rapid TBMs are used. Other flammable gas requirements from 29 CFR 1926.800 are as follows:

When an air sample indicates—	*The necessary action is—*
5% or more of the LEL	Increase ventilation, control gas.[1]
10% or more of the LEL	Suspend hot work such as welding or cutting.
20% or more of the LEL	Cease work, cut power, withdraw employees.[2]

[1]A flammable gas concentration of 5% of the LEL or higher (0.25 vol % of methane) indicates an action level to take improved safety measures. OSHA requires steps to increase ventilation air or otherwise control the gas in such cases. However, it is wise to also implement a better monitoring program and training for workers. Any ventilation improvements should generally be permanent, the goal being to consistently operate below 5% of the LEL if at all possible.

[2]Detector warnings and equipment shutdowns triggered by high gas levels indicate an *immediate* need for better ventilation.

Handheld detectors are used to check for gas in any location. However, a peak emission can be missed because readings are taken at infrequent intervals. Fixed-site monitors operate continuously and can identify emission peaks and shut off electrical equipment when the methane level is excessive. Fixed-site monitors typically have two or more heads; the important ones are near the face and/or the muck discharge point.

Monitor heads should not be located where they are directly bathed by a stream of fresh air; this can prevent gas from reaching the head. Also, regular cleaning of monitor heads is necessary. Dirt-clogged heads can fail to detect methane, so monitor heads should not be located where muck spatter or water sprays will make them ineffective.

As part of a monitor check, use a “shutdown test” to ensure that the fixed-site monitor is hard-wired into the tunnel electrical system properly. Bathe each monitor head with a gas mixture that has more than 1% methane, and check to see that the TBM and its auxiliary equipment shut down as they should.

Do the shutdown test as excavation begins, and then a few more times over the course of the project.

[10]*Code of Federal Regulations.* See CFR in references.

ELIMINATING IGNITION SOURCES

Electrical equipment in tunnels may or may not be explosion-proof, depending on the level of the hazard. The OSHA safety and health standards for underground construction [29 CFR 1926.800] contain the applicable requirements and definitions. OSHA has two hazard classifications, denoted “potentially gassy” and “gassy.” These are based on the results of air monitoring, on the local geology, on whether there has been a flammable gas ignition, and on whether there is a connection to another tunnel that is gassy. For the air monitoring, the classification trigger level is 10% of the LEL, and the specific classification depends on the length of time for which this gas level or higher is observed. Tunnels so classified must meet additional ventilation, gas monitoring, and equipment requirements. Some states have their own regulations as well.

It was mentioned earlier that a flammable gas concentration of 5% of the LEL or higher should be regarded as an action level to improve safety. Taking action at the 5% level will improve the chances that the 10% level will not be reached.

In the event that a large pocket of gas is encountered, some equipment may still be used. At a minimum, this includes fans and telephones. However, such equipment must always be explosion-proof.

Tunnel contractors must bear in mind that providing explosion-proof equipment does not in itself eliminate the possibility of a spark source. For instance, sparks generated by cutting tools striking rock often have enough energy to ignite an explosive mixture. Welding or striking a match to light a cigarette can have the same effect.

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 fault tree, they 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 lead to an explosion (Table 14–1). As evidenced in Table 14–1, most initiating events involve a human factor rather than an engineering specification. In other words, safe conditions require the everyday vigilance of those working underground. This does not undermine the importance of good engineering design, only 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 a no-smoking rule and more thorough gas checks during welding.

Table 14–1.—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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