CHAPTER 7.—SMOKE AS AN ESCAPE AND BEHAVIORAL ENVIRONMENT

This chapter focuses on smoke as it relates to escape from underground mine fires. Among the topics discussed are the measurement of visibility in smoke; smoke-related hazards such as the production of CO, hydrochloric acid (HCl), or other byproducts of combustion; and miners' personal experiences while escaping through smoke.

Smoke Measurement and Visibility

In general, smoke consists of hundreds of thousands of very small particles. These particles have some "size," usually expressed in terms of their diameters, and they have some concentrations, usually expressed either in the number of these particles per unit volume or the total mass of the particles per unit volume.

Humans cannot see individual smoke particles because they are too small. Similarly, "umber concentrations" and "mass concentrations" of smoke particles do not have much meaning to people unless they are trained technically. Still, individuals know that they can see smoke, independent of all the technical jargon used to describe it. Also, they know that when the smoke level gets too high, it is no longer visible. In fact, nothing is visible because the smoke absorbs all of the light in its surroundings.

The eye is only sensitive to light in the wavelength region from about 400 nm to about 700 nm. The maximum sensitivity of the human eye is to light that has a wavelength of about 555 nm. It is important to know how the eye responds to light because if its response is known, it is possible to use a light detector that has almost the same response as the eye. Such a detector can then be used to quantify the visible characteristics of smoke because it responds in the same manner as the human eye.

Smoke is visible because it either scatters or attenuates (diminishes) light. In some instances, smoke is visible because the smoke particles reflect light which is then detected by the eye. The eye actually "sees" an intensity of light that has been reflected from a cloud of smoke particles. Imagine shining a flashlight into a cloud of smoke. Someone off to the side can actually "see" the beam of light as it traverses the smoke cloud. This is called scattering. Smoke is also visible because it attenuates light. Imagine having someone shine a flashlight into your eyes. As smoke begins to build up along the beam of the flashlight, the light begins to dim. The smoke is visible because it is now reducing the intensity of light that falls upon the eye. As the smoke level increases, it is said to obscure our visibility. When the beam is no longer visible, the smoke obscuration is said to be 100%. In other words, none of the light energy from the flashlight makes its way through the cloud of smoke. Another way of saying that the obscuration is 100% is to say that the transmission of light through the cloud is zero.

Although it is possible to measure the light that is scattered by smoke, most studies usually measure the amount of light that is transmitted through a cloud of smoke. There are three basic reasons for measuring light transmissions rather than the amount of light that is scattered. First, the intensity of scattered light depends on many factors, such as the size of the smoke particles, the angle at which one measures the scattered light relative to the direction of the light beam, and also the attenuation of the scattered light in the space between the beam and the light detector. Second, the amount that smoke obscures light is a direct measure of a visibility hazard. Obscuration by smoke is one hazard that is clearly evident in mines. Imagine a 100-watt lightbulb 3 m away. If the smoke is dense enough so that the effective power of the bulb is only 1 watt, then the obscuration would be 99%. If the cloud of smoke is so dense that obscuration is total, then it becomes impossible to see. Smoke from an unwanted fire that reaches this level of obscuration represents a critical, life-threatening situation because it becomes impossible to use one's eyes to escape. Finally, the measurement of light transmission allows for characterization of smoke by a single parameter. This parameter is called the "optical density" and is derived from the amount of light that is transmitted (T), at a given intensity, through a smoke cloud over some path length (L):

$$D = \frac{1}{L} \log \left(\frac{1}{T} \right)$$

Optical density is used to assess hazards of smoke and levels of detectability. It is important to remember that this transmission is measured using a light detector that matches the response of the human eye.

Smoke Hazards, Visibility in Smoke, and Human Response in Smoke

The chemical composition of smoke particles depends, in part, on the material that is burning. Some materials may produce gas, or gases that attach to smoke particles, which can cause the eye to tear, even at moderate levels of obscuration. Smoke from a fire is also breathed into the lungs, where some of the smoke is deposited before it can be exhaled. The smoke and its chemical composition can irritate the respiratory system and also contain elevated levels of toxic gases or compounds that attach to the smoke particles. All of these effects are difficult, if not impossible, to quantify because of the many combustibles that can burn and produce adverse effects.

Several studies have been conducted to assess the effect of smoke on humans, especially with regard to ability to escape from smoke-filled environments. Jin [1981] reported the results of a series of studies that investigated emotional instability of individuals in smoke from fires. Using human subjects, Jin measured both physiological and psychological response to smoke produced from smoldering wood that was uniformly introduced and dispersed throughout a test room. For the experiments, individuals were seated one at a time at a table in a test room with a floor area of 5 by 4 m (16.4 by 13.1 ft), with no windows and one door. At the table, each person was asked to manipulate a steadiness tester which consisted of a metal plate with four holes of graduated sizes, and a metal stylus. Both of these devices were connected to recording instruments. Each person was told to thrust the stylus into the holes in a specific order, but trying not to touch the sides of the holes with the stylus. The smaller the diameter of the hole, the harder the subject had to concentrate to avoid contacting the sides of the hole. After completing one cycle of operating the steadiness tester, which required about 30 seconds, each person stood up from the chair, walked to the other side of the room, pushed a button switch located on another table, and then walked back to the table on which the steadiness tester was located. The button switch ensured that test subjects walked to the other end of the room after each cycle. Each person walked a total distance of approximately 10 m (33 ft).

In the experiment, Jin divided subjects into two groups. The first group, composed largely of fellow researchers, received a pretest briefing in which individuals were made familiar with the layout of the test room and were also informed that the smoke being used was harmless. The second group, which constituted subjects from the general public, was placed in the test room without being familiarized with the area or informed of the smoke's nontoxicity. For both groups, few individuals had previous experience with exposure to smoke from fire.

Jin noted that as the smoke density increased, fear of the smoke coupled with irritations of the eyes and throat impeded individuals' ability to concentrate on the task of operating the steadiness tester. This resulted in increased frequency of contacts between the stylus and edges of the holes. Human response levels were correlated with the optical density of the smoke produced by assessing the number of stylus contacts on the steadiness tester.

Results indicated that, for the general public, most individuals began to experience emotional effects when the smoke optical density reached 0.044 m^{-1}. In contrast, most subjects in the group of researchers began to show emotional fluctuation at smoke densities of 0.15 to 0.24 m^{-1}. It is interesting to note that, while all individuals were told they would be advised when they could leave the test room, 15 people out of the general population group fled the room to escape the smoke before their test run was completed and prior to the smoke density reaching 0.22 m^{-1}.

Following these experiments, some of the participants were interviewed regarding their experience. Jin generalized the comments for the general public test subjects as follows:

> Smoke itself didn't scare me much when it was thin...irritation to the eyes and throat made me nervous, and when I thought of the smoke getting still thicker...I was suddenly scared of what's going to happen next.

Jin concluded that the data from these individuals could be treated as being equal to data that would be obtained from a group of people who are unfamiliar with the internal layout of a building.

Among subjects from the group of researchers, most individuals became more anxious about physiological factors such as throat and eye irritation rather than the psychological element. As mentioned by one participant, "When I got the signal to end the test, irritation and suffocation were near the limit I could physiologically stand." Jin concluded that—

1. For a person unfamiliar with the escapeways and exits of a building, that individual's ability to escape safely from a fire within that building is severely reduced when the smoke optical density exceeds 0.066 m^{-1}.
2. If an individual is familiar with the escapeways and exits of a building, that person's ability to escape safely is severely reduced when the smoke optical density exceeds 0.22 m^{-1}.

During these tests, the levels of CO were continuously measured, reaching a peak value of 50 ppm at the end of each test (D . 0.305 m^{-1}), which equates to an optical density/CO ratio (D/CO) of 6.10×10^{-3} $(ppm \cdot m)^{-1}$. At these levels of optical density, smoke obscuration is severe enough to reduce visibility to near zero levels. For instance, at $D = 0.066\ m^{-1}$, the range of visibility is about 13 m (42.5 ft) while at $D = 0.22\ m^{-1}$, it is approximately 4 m (13 ft). Because of this, Jin referred to these optical densities as critical values at which the smoke becomes untenable due to the total impact of the smoke on the human response, which includes reduction in visibility and other physiological and psychological effects.

Other studies have chiefly focused on visibility in an effort to determine critical limits for optical density in smoke. Rasbash [1975] conducted experiments in which subjects, wearing breathing apparatus, focused headlamps that were held waist-high on a target. The target was a black letter "C" on a white background. As smoke was introduced, visibility values were recorded based on individuals' ability to see the target. Rasbash concluded that the visibility limit in smoke occurs at an optical density value of 0.08 m^{-1}, which corresponds to a distance of about 10 m (33 ft). Babrauskas [1979] studied escape from rooms containing burning furniture. Because of the short travel distance used in these experiments, Babrauskas used an optical density of 0.5 m^{-1} as an obscurity criterion for escape. Heyn [1977] obtained similar results when measuring the relation between smoke density and visibility at the Tremonia Experimental Mine in Germany. For these experiments, Heyn conducted tests using small conveyor belt fires which resulted in visibilities of only a few decimeters.

Miners' Emotional and Physiological Experiences in Smoke

Miners who escaped the three mine fires experienced psychological and physiological effects similar to those noted by Jin [1981], as well as visibility problems like those noted by Heyn [1977] and others. One analysis of the data revealed that a number of workers experienced trouble wearing their SCSRs [Brnich et al. 1992]. Twenty-nine of the miners who escaped these fires (63%) reported having difficulty breathing with their SCSRs, largely because they were unfamiliar with how an SCSR worked. As a result, 27 of the 29 said they either took the mouthpiece out to catch a breath or "breathed around" the mouthpiece in smoke.

Many of the miners interviewed at each of the three mines had some prior experience in dealing with fires underground. Often, though, these fires were small ones, such as equipment cable fires, hot belt rollers, or hot trolley wire hangers along the haulage. These types of fires generate heavy smoke in some cases, but rarely result in the need for miners to escape through smoke-filled entries. Consequently, many of the miners who were caught inby the three fires had never escaped through smoke.

Most of the miners who escaped the fires at Adelaide and Cokedale Mines were unfamiliar with the escapeways leading from their working sections. About 3 weeks before the fire at Adelaide, the company realigned section crews in an attempt to boost morale and improve productivity. Many miners were assigned to sections they had never worked on before. As a result, a number of these reassigned workers had not been given an opportunity to walk the escapeways from 1 Right, 2 Northwest, and 3 Left sections in order to become familiar with them.

Personnel caught inby the fire at Cokedale Mine worked on a maintenance shift and were not assigned to any particular section. On the night of this fire, these miners were in the process of setting up a new production section in 8 Face Parallels or doing maintenance work in 7 Butt. All individuals were working in an area of the mine with which most were unfamiliar, and, like miners at Adelaide, many of them were not familiar with the escapeways leading from this area of the mine. Unlike workers at the other two mines, miners who escaped the Brownfield Mine fire were working on their regular sections and knew their escapeways, but chose alternative routes in an attempt to elude heavy smoke.

As mentioned earlier, Jin [1981] concluded that a person's ability to escape by an unfamiliar route is severely reduced when the smoke optical density equates to a sight distance of about 42 ft. Persons familiar with escapeways have their ability hampered when the smoke optical density equates to about 13 ft of visibility. Based on Jin's findings, it is reasonable to expect that miners who were not familiar with their escapeways would have been at a disadvantage compared to those who knew the travel routes. However, individuals who escaped the mine fires reported visibility distances that were often far below those calculated from Jin's results. Consequently, familiarity with escapeways did not necessarily help miners navigate, due to the overall poor visibility. Visibility distances estimated by workers ranged from less than 2 ft in primary escapeways, track and belt entries (mean 7.3 ft) to as much as 60 ft in return airways (mean 47.5 ft). In addition, some miners did not expect the smoke they encountered to be as thick as it was. A wireman, who was moving a power center in 7 Butt at Cokedale Mine when the fire occurred, described his experience:

> I didn't expect it to be that thick...they show you movies, you can get down on your hands and knees and crawl out. I don't think you could do that...you could see it coming right off the runaround.

Miners characterized smoke in various ways by both its color and thickness. In areas where the smoke was lighter, a worker described it as having a bluish-gray color and being "like...more just like a filtering smoke." Another miner, traveling with his crew through a return airway, said he could see about 30 to 40 ft and that walking through the smoke was like walking through a light fog. Other workers, however, encountered thick, heavy smoke as they escaped. Two miners described the thickness of the smoke they encountered. A utilityman from Adelaide Mine said:

> You couldn't see...it was just like, I'll tell you what it reminded you of... like riding in behind...a bulk duster for rock dusting.

Another utilityman, also from Adelaide Mine, was traveling with his buddies through the secondary escapeway located in the right-side return aircourse of 3 Left. When they reached an overcast where the return crossed the intake, the group encountered heavy smoke:

> I walked up there to the overcast and I stepped right into it. And it was like a black wall. It was like burning 50 tires and trying to walk through it...and I said, "We can't go that way." So we walked out and there was some—I know there was doors in those overcasts. I said, "The intake's here someplace. All we've got to do is find it." And you'd open up the door and it'd just billow out; and you'd open another door and it would

> billow out...we opened up [one] door, it looked like it was a black river running by. That's how thick it was.

A miner from Brownfield Mine could not find the mandoor in a stopping because of the thick smoke:

> The [stopping] was probably on the other side of these props, but I couldn't see it. I couldn't even see the door, that's how thick it was. I put my hands out...and I couldn't see the end of my fingers.

For miners escaping in heavy smoke, navigating through the mine was difficult because of the poor visibility. At Brownfield Mine, the smoke was so heavy that a foreman actually walked into the belt structure while attempting to make his way to the other side of 6 West mains to check for fresh air in the No. 7 intake:

> So I went out through this door, and I'll tell you the smoke's so thick right here I walked into the belt. I couldn't see it.

Regardless of whether they followed designated escapeways or not, miners used various (and in some cases highly creative) means to keep themselves together to prevent becoming separated and to navigate through the smoke. Workers escaping from the 7 Butt section at Cokedale Mine held on to one another as they attempted to stay together while crossing through the track entry to get into the return:

> Smoke was coming on the tracks, we reentered on the tracks there by the spray pump, smoke was real bad we had to hang on to each, one another like a bunch of elephants.

To guide themselves, miners escaping through smoke followed objects they encountered in the mine entries, such as stopping lines, rows of props, old track, and water lines. At Adelaide, the 1 Right crew was led out by a utilityman who was a former fire boss. He led his buddies down the left return airway of old 8 Left to the 2 Northwest left return and then continued outby. For the entire distance, the utilityman followed the stopping line located between the intake and return entries knowing that, by keeping the stoppings on the left, his crew would be less likely to make a wrong turn. A maintenance foreman and mechanic, working in the 6 West section of Brownfield Mine, were following the primary escapeway from the section. Hoping that there would be lighter smoke in the secondary escapeway, the two miners, along with a State electrical inspector, went through a door into the left-side return aircourse. Although the group encountered moderate to heavy smoke in the return, the foreman knew that the return airway would lead them directly past the fire area. The foreman, therefore, decided to continue traveling in the return, since he could follow a row of posts in this entry to guide himself. "I mean, the return is double-timbered. I just stayed between the props and went." The crew from the 5 South section at Brownfield Mine also traveled through the 6 West left return and used the props to guide themselves:

> We just stayed—we knew that the return went straight down because we'd walked it before. So we just stayed in the 6-foot walkway between the posts, and more or less we were walking from overcast to overcast.

A group of miners who were escaping from the 8 Face Parallels at Cokedale used a unique method to help them find their way. The crew, being led by a general inside laborer (GIL), made their way to the secondary escapeway located in the right return aircourse of 8 Face. Because the escapeway followed entries that were mined more than 35 years earlier, the passageways had deteriorated. Miners had to cross over roof falls and contend with low clearances due to floor heave and low crossbars. Although the escapeway was marked with reflective signs, miners reported that it was difficult to see them due to the heavy smoke and the fact they had to bend over to walk. To more easily navigate through the escapeway in the smoke, the GIL who led his buddies from the 8 Face Parallels area did not try to follow the reflective markings in the escapeway. He instead followed the footprints left by fire bosses who had conducted prior hazard examinations of the area, knowing that the footprints would lead him out of the mine:

> As you're walkin', you're not walkin' on a—you're goin' up and down crawlin' [over falls] this and that—people were, you hear people goin' "ow, ow" hit their head...And I just kept lookin' at the ground and lookin' at footprints and I did catch I did see footprints. Reason I say I was lookin' at footprints and not the signs was why keep bangin' your head needlessly. If you can't see 2 feet, how are you gonna possibly see that sign—I don't care whether it is red or green, you can't see it. The footprint is the closest thing to you that also meant to me—these [returns] have to be walked periodically. When I see footprints, I felt better. Somebody was through there already there is only one set goin' out. So chances are that if there was a return set of footprints, I would think somebody had to turn around because it's blocked. Being there was only one set, there's got to be an opening up ahead somewhere.

While some miners had the "luxury" of being able to follow markers or other objects to guide themselves out of the mine, the smoke was so thick in some cases that miners could not follow objects visually. Instead, they had to feel their way along in places in order to find their way out. Miners felt their way along water lines, posts, the mine's ribs, and other features in order to make their way to safety. At Brownfield Mine, a Federal mine inspector was escaping with the crew from 4 South and was part of a group of four miners making their way off the section by traveling the belt entry. During their escape, the group began to break up after a miner from the crew started having trouble walking. At this point, fearing he would run out of oxygen in his SCSR, the inspector left the group and continued on his own. When he reached the mouth of the section, the inspector decided to go through a door in an overcast and check the intake escapeway for smoke. Upon seeing that it was still filled with heavy smoke, he came back into the belt entry, which also contained heavy smoke, and attempted to continue his escape. Unable to see, the inspector felt his way along a machine guard on the belt drive:

> The belt drive is entirely guarded with chain link fence...as I come out of the overcast area, it seemed like the first thing, I reached up as I came out and the chain link fence was there. I really couldn't see but I just hand over hand followed the chain link fence so I wouldn't trip on anything.

In his experiments, Jin [1981] noted that as smoke density increased, individuals began to fear the smoke and experienced physical irritation as well as an elevated apprehension that severely hampered their concentration. Miners who escaped the three mine fires reported psychological and physiological effects similar to, and in some cases more dramatic than, those experienced by participants in Jin's experiments. Of the 48 miners interviewed, nearly one-half of them (48%) reported experiencing some level of emotional instability as they made their way through the smoke-filled escapeways.

Several miners said that they became frightened when they first encountered smoke. In some cases, fear of smoke severely hampered miners' ability to concentrate and perform motors tasks such as those associated with donning an SCSR. The wireman, who had been in the 7 Butt section of Cokedale Mine, was riding in a jeep with the section boss when they encountered smoke in the 8 Face track entry:

> We were in the jeep, and we hit smoke. I got all scared you know, all, what the hell we going to do, you know, all this smoke...And I was on the jeep, and [the boss] said, "Get your SCSRs on." And I...opened mine up and I was like shakin' like a leaf, couldn't get the damn thing

> open. And [the boss]...said, "Here, pop this, stick this in your mouth..." I mean, I couldn't get the damned thing, I was so damned scared I didn't know what else, I didn't know what the hell to do, you know.

Other miners said they began to fear the smoke when it became thick and heavy. Apprehension about the smoke caused one of the shuttle car operators at Adelaide Mine to experience difficulty breathing, even though he was wearing an SCSR and was protected from the smoke. When his crew encountered heavy smoke billowing from an overcast that they had to cross at the intersection of 3 Left and 2 Northwest Mains, this miner experienced tremendous anxiety:

> We went into that smoke and I couldn't breathe and was gagging on that self-rescuer. I couldn't breathe any at all...I couldn't go in [that smoke]. I guess it may be psychological or something about being in that smoke or something. I couldn't breathe at all. In [the smoke] I was gagging but as soon as I would come out of there, it seemed like I was breathing better, a little bit better.

Because of his experience, the shuttle car operator chose not to follow his buddies into the heavy smoke at the overcast. Instead, recognizing where he was, he decided to follow another route that led him across 2 Northwest Mains and down the right-side return escapeway to a point outby the fire. This decision is significant because several of the miner's buddies, believing him to be lost, risked their lives by going back to the overcast to look for him after everyone had reached safety.

While some miners became afraid in the smoke, others became confused and disoriented. This inhibited some miners' ability to think clearly and respond functionally to the situation. The Federal mine inspector, who escaped from 4 South at Brownfield Mine, had conducted numerous inspections in the sections off 6 West Mains and was moderately familiar with the layout of that portion of the mine. Nevertheless, he reported becoming disoriented and confused in the heavy smoke, especially toward the end of his ordeal as he made his way from the belt entry to the track:

> As soon as I found the crosscut, I went in because I didn't want to miss it and I went to the end of the crosscut and run into a permanent stopping. Well, I started looking for the door and it seemed like I was lost. I wasn't lost but it seemed like I was lost because I got sort of that feeling, well, I know that door is here but I just couldn't find it.

After getting into the track entry and traveling another crosscut, the inspector reported seeing lights ahead of him, but he was not sure of their significance

"I could see lights ahead of me. I could see these lights...[but] the lights really didn't mean anything to me."

The 4 South section mechanic was in the same escape group as the Federal inspector. After the escape group broke up, the mechanic continued traveling outby along the beltline. Even though the belt entry led directly out of the section to 6 West mains, the mechanic became confused and disoriented in the smoke:

> I didn't know my way out of there. I lost all orientation how to get out of there. I knew my way out, but I forgot. It was just a panic thing.

Jin [1981] noted in interviews with test subjects that, as the smoke became thicker, some individuals became apprehensive as they wondered what would happen next. Based on these findings from a controlled experiment, it is not surprising that miners who escaped the fires experienced similar mental anguish when thoughts of what lay ahead entered their minds. Miners who experienced emotional instability reported thinking about many different things as they made their way through the mine. The foreman of the crew escaping from 8 Face Parallels said, "Your heart's thumping and all kinds of goofy crap's going through your head." Some miners thoughts turned to their families. A brattice-man who escaped with the crew from 3 Left at Adelaide Mine said he thought about never seeing his family again: "I kept thinking, I want to get out. I don't want to die in here, I want to see my wife and kids."

Other miners experienced thoughts of not escaping the fire and dying in the mine. The shuttle car operator, who left his crew at the overcast to explore another escape route, said, "I thought I was going to die right there in that smoke." Several miners said they thought about the Wilberg Mine disaster and wondered to themselves if they were going to meet the same fate as their fellow miners did in December 1984:

> But what was in everybody's mind was the thing that happened at Wilberg. Myself, I thought we wasn't going to go, to get out.

> And my personal thoughts were that it was a Wilberg disaster, and that's all that was in my mind.

While some miners only thought about the possibility that they were going to die in the smoke-filled entries, others had virtually given up hope. After checking the left-side intake of 6 West Mains at Brownfield Mine and seeing that it was full of smoke, a roof bolter operator from 5 South made his way back to where several other miners were waiting:

> And there was a couple of rock dust guys right there. I sat down with those rock dust guys and I figured this is where I bunk—this is it. I was just going to say goodbye to the world. I couldn't see anything.

In another instance, the miner operator from 4 South at Brownfield Mine reported being also ready to die. He had been evacuating with the section mechanic, the Federal inspector, and another miner. While traveling along the 4 South belt entry, the miner operator experienced great difficulty. He was having problems breathing with his SCSR, became disoriented and unable to see in the smoke, and kept falling down in the mud. After falling down for one last time, and after his buddies had left him, the miner operator gave up:

> So I was there by myself and I was down in the mud. I remember just stopping a couple of times and just, you know, wishing it would get over with, almost wishing I'd die or something, just to get it over with. It was a horrible feeling.

It is evident from these accounts that miners experienced great emotional trauma while escaping through the smoke-filled passageways. In some cases, miners' ability to concentrate, make informed choices, and take appropriate actions during their escape was severely hampered by the need to deal with emotional effects of the smoke.

Besides having to cope with the psychological effects of smoke in their escape environment, many miners had to contend with physiological elements as well. Smoke clouds carry CO as well as sensory irritants, both of which are byproducts of combustion. As mentioned earlier, Jin [1981] measured CO levels and calculated the ratio of CO to optical density as D/CO. It is worth noting that the ratio observed by Jin ($D/CO = 6.10 \times 10^{-3}\ (ppm \cdot m)^{-1}$) is identical to the value quoted by Litton [1989] for smoldering wood. Therefore, depending on a person's familiarity with his or her surroundings during a fire, the levels of CO that are present when smoke visibility reaches its critical level lies somewhere between 10 and 35 ppm.

Relationship Between Critical Levels of Smoke and CO

In Jin's experiment, these critical levels of optical density were measured for wood smoke. Depending on the actual material burning and the resultant characteristics (both physical and chemical) of the smoke produced, these critical values could increase or decrease. Clearly, a critical level of optical density at which the range of visibility is reduced to •1 m represents an upper limit. The range of visibility is defined as the distance at which the light obscuration exceeds 86% (or, the transmission is less than 0.14). At a 1-m visibility range, the critical level of optical density is 0.92 m^{-1}. This value should be considered as an absolute maximum value based solely on reduced visibility.

Using the data of Litton for the ratio of CO to smoke optical density, it is interesting to compare the expected levels of CO that would be present at the values of optical density equal to 0.22 m^{-1} (the maximum critical level reported by Jin) and 0.92 m^{-1} (the absolute maximum), discussed above. These levels are shown in table 7.1 for smoldering fires and in table 7.2 for flaming fires.

Data have been acquired in full-scale tests at Lake Lynn Laboratory which demonstrate the levels of visibility that occur as a function of the CO level. In these tests (see figure 7.1), placards were placed at fixed distances from a camera and irradiated by a white light. As time progressed during these tests, the smoke level increased, eventually obscuring the placards. As these placards disappeared in the smoke, the levels of CO at the times of their disappearance were measured.

Figure 7.2 indicates the visibility (in meters) measured as a function of the CO level (in parts per million). The solid line indicates the level of visibility predicted from smoldering coal fires, while the dashed line indicates the level of visibility predicted from flaming coal and styrene-butadiene (SBR) belt fires. It is important to note that during the large-scale experiments, the initial levels of CO and smoke come from a smoldering coal fire while the later levels come from a flaming coal and conveyor belt fire. In figure 7.2, the level of CO at which the coal fire ceases to smolder and begins to flame is indicated by the arrow. The importance of these data is apparent: significant reductions in visibility occur at relatively low levels of CO (10-20 ppm).

Table 7.1.—Visibility as a function of CO level in smoldering fires

Combustible	ppm CO at $D = 0.22\ m^{-1}$	ppm CO at $D = 0.92\ m^{-1}$
Wood	36.0	150.0
Coal	9.0	38.0
SBR conveyor belt	2.5	10.5
PVC conveyor belt	3.0	12.5
Neoprene conveyor belt	7.0	29.0
PVC line brattice	11.0	46.0

Table 7.2.—Visibility as a function of CO level in flaming fires

Combustible	ppm CO at $D = 0.22\ m^{-1}$	ppm CO at $D = 0.92\ m^{-1}$
Wood	56	234
Coal	17	71
SBR conveyor belt	19	79
PVC conveyor belt	42	176
Neoprene conveyor belt	32	143
Transformer fluid	7.5	31

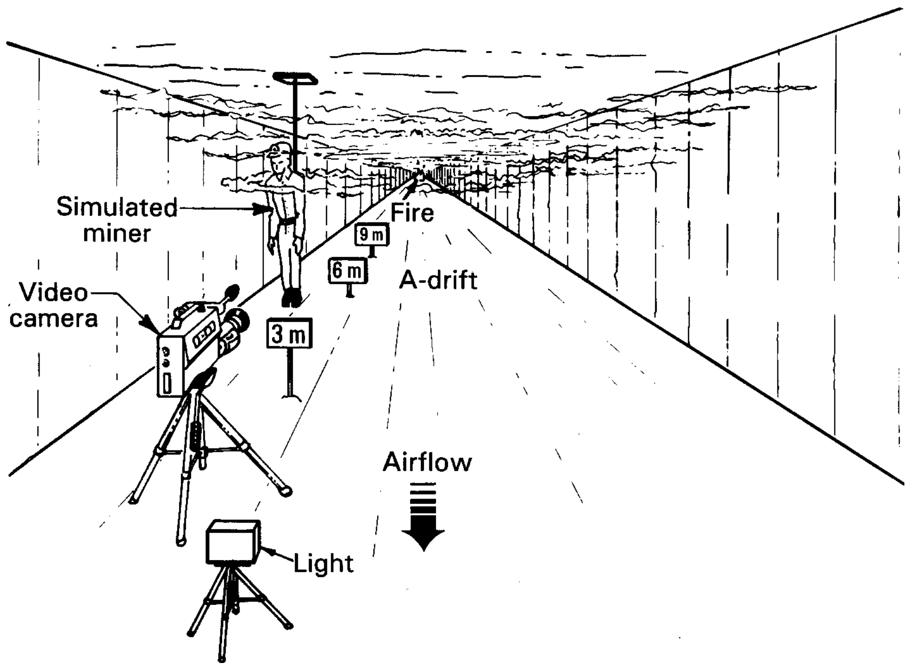

Figure 7.1.—Depiction of experimental setup in A-drift at Lake Lynn Laboratory.

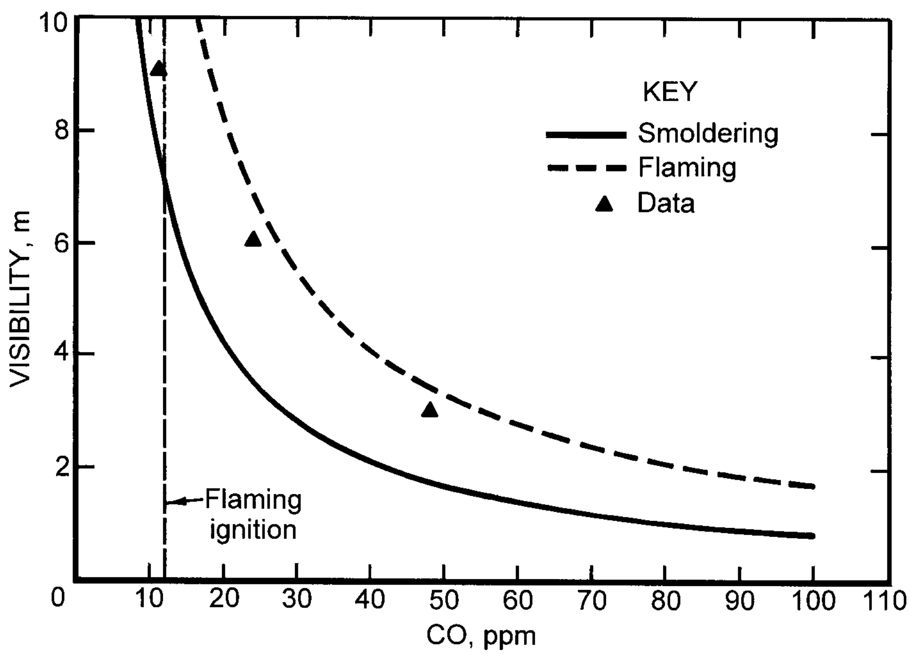

Figure 7.2.—Visibility measured as a function of CO level.

Depending on the material burning, other toxic and irritating elements can be produced. For conveyor belts, in particular, the generation of HCl vapor due to chlorine in the belt, as either a component of the base polymer or as an additive to make the belt more flame-resistant, is an example of such an irritant and also represents a potential toxic hazard in addition to the CO produced. Smith and Kuchta [1973] have measured the levels of HCl and CO produced from flaming SBR and polyvinyl chloride (PVC) conveyor belts. They found that the ppm of HCl is equal to 0.105 times the ppm of CO for SBR belts and 0.205 times the ppm of CO for PVC belts. Similarly, for smoldering conveyor belts, Egan [1992] finds that the ppm of HCl is 0.30 times the ppm of CO for SBR belts; 0.40 for PVC belts; and 1.0 for neoprene belts.

For CO, the level quoted as being immediately dangerous to life and health (IDLH) is 1,500 ppm; for HCl, 100 ppm [Mackinson et al. 1980]. If one uses these numbers as critical values and assumes them to be additive, then a toxic environment is produced downstream of a fire when the following condition is satisfied:

$$\text{TOX} = \frac{\text{ppm CO}}{1{,}500} + \frac{\text{ppm HCl}}{100} \geq 1.0$$

Using the levels of HCl produced relative to the CO, tables 7.1 and 7.2 can be used to generate values of TOX at the indicated levels of smoke optical density. These are shown in tables 7.3 and 7.4.

Table 7.3.—Values of toxicity at indicated levels of optical density in smoldering fires

Combustible	TOX at $D = 0.22\ m^{-1}$	TOX at $D = 0.92\ m^{-1}$
Wood	0.024	0.100
Coal	0.006	0.025
SBR conveyor belt	0.009	0.038
PVC conveyor belt	0.014	0.059
Neoprene conveyor belt	0.075	0.313

Table 7.4.—Values of toxicity at indicated levels of optical density in flaming fires

Combustible	TOX at $D = 0.22\ m^{-1}$	TOX at $D = 0.92\ m^{-1}$
Wood	0.037	0.155
Coal	0.011	0.046
SBR conveyor belt	0.033	0.138
PVC conveyor belt	0.114	0.476
Transformer fluid	0.005	0.021

Only a flaming PVC conveyor belt produces toxic products of CO and HCl to such an extent that the combustion products begin to pose a severe toxic hazard. This occurs at the maximum allowable level of optical density. It is clear from tables 7.3 and 7.4 that the presence of smoke poses a more severe impediment to survivability and eventual escape from fire than the toxicity of the gases produced.

It is interesting to note several subjective observations regarding smoke irritation made by Kissell and Litton [1992] during a conveyor belt fire test. In levels up to 40 ppm CO, test subjects experienced some labored breathing and mild eye irritation. When CO levels reached 80 ppm, individuals experienced hard breathing and stinging of the eyes. At 160 ppm CO, subjects found it very difficult to breathe and reported severe eye irritation. Participants also stated that they could barely see. These results indicate that severe sensory irritation can occur at CO levels below those that would cause carboxyhemoglobin danger.

Experiencing Smoke Density and Physical Discomforts

The studies reported here indicate that smoke density and the physical irritants produced pose a greater threat to escaping miners than the levels of CO and other gases, which do not reach toxic levels when the critical optical density is reached. In the three mine fires, however, some miners could have been in danger had CO levels been high enough. The reason is that most of the miners who escaped did not really understand the dangers that combustion products can pose. Miners were asked if they thought about the presence of CO during their escape. One miner provided his thoughts:

> Well, the way I was thinking, we was on the intake side...and was just starting to get some smoke. When we went in the return, it wasn't even heavy as that, so why worry—you know what I mean—as long as you can't see the smoke.

Although research has shown that the levels of CO and HCl do not appear to always reach toxic levels in thick smoke, a number of miners reported experiencing moderate to severe physiological effects, particularly sensory irritation. Slightly more than one-third (34.8%) of the miners who escaped said they experienced various problems such as choking, coughing, and eye irritation. Some miners said that they traveled barefaced through smoke before donning their SCSR and subsequently inhaled smoke. A mechanic at Cokedale, escaping with his buddies from 8 Face Parallels, described his experience with smoke inhalation:

> The section was really starting to fill with smoke, I had never had such a dry mouth or throat; it's almost like you could spit dust. I mean it's so

> dry, that's the one thing I remember vividly. And at that point, the smoke had started to uh, to overcome me. I was choking, coughing, and gagging and at that point, I took it upon myself to use my small [filter self-] rescuer.

Some miners experienced eye irritation from particulates in the smoke. A trackman who escaped from 7 Face at Cokedale said, "My eyes were affected somewhat. They were extremely red when I got outside."

It is understandable why miners experienced emotional instability during their escape through smoke from these fires. However, one might question why more than one-third experienced physiological problems since miners would have been offered respiratory protection from either their SCSR or FSR and eye protection from the goggles contained in their SCSR. These problems are easily explained: besides removing the mouthpiece to breathe, as mentioned earlier, nearly 48% of the miners who escaped also took the mouthpiece out in smoke to talk. Subsequently, miners inhaled smoke and various contaminants which caused them to experience breathing discomfort. The interviews also revealed that few miners wore the goggles supplied with their SCSR to protect their eyes. Many of the miners said that the goggles fogged quickly and hampered their vision. As a result, more than 63% of the escaping miners said they did not wear the goggles for that reason.

One of the most interesting problems that affected miners' emotional stability during escape was the unanticipated presence of smoke in certain areas of the mine. Ventilation systems can be extremely complex and made up of four or more air shafts, tens of miles of aircourses, and hundreds of stoppings and overcasts. This is especially true in large, older mines such as Adelaide, Brownfield, and Cokedale, where air must travel several miles from an intake shaft through intake entries to the working sections and back to the shaft via return aircourses. Where air must traverse such considerable distances through older aircourses, excessive air loss is common. Depending on the mine, it is not unusual to lose between 30% and 50% of the air before it ever reaches the working sections [Mosgrove 1981; Stefanko 1983].

Air loss is due to a variety of reasons, including frictional resistance in the aircourses and leakage across stoppings and overcasts. In a mine fire, air leakage across ventilation devices can result in significant amounts of smoke making its way into escapeways and other entries. To demonstrate, a U.S. Bureau of Mines investigation by Litton et al. [1991] studied the detection of conveyor fires. For this experiment, researchers placed a pile of coal beneath a section of SBR belt. Air velocity in the test tunnel, designed to simulate a single mine entry, was 10 m/sec (200 fpm), while the air quantity was 7.6 m^3/sec (16,000 cfm). Researchers then monitored combustion products in the air 20 m (65 ft) downstream as the pile of coal smoldered, burst into flame, and then set the SBR belt on fire. Data obtained from this study were then used to calculate contaminant and visibility levels, resulting from air leakage across stoppings, in a hypothetical escapeway that might be located adjacent to an entry containing a fire [Kissell and Litton 1992]. These calculations reflect conditions 60 minutes into the fire. The concentration of contaminants in the escapeway (C_e) was determined using the dilution equation:

$$C_e = C_f \left(\frac{Q_L}{Q_e + Q_L} \right),$$

where C_f is the contaminant concentration in the fire entry, Q_L is the quantity of air leakage, and Q_e is the quantity of air in the adjacent escapeway. Assuming a Q_e of 9.4 m^3/sec (20,000 cfm) in the escapeway, a CO concentration (C_f) of 2,700 ppm in the fire entry, and a Q_L of 0.94 m^3/sec (2,000 cfm) across the stopping line, a CO concentration of 245 ppm was calculated for the escapeway. A similar calculation was performed to determine the optical density in the adjacent escapeway. Using the optical density value, a visibility of 0.3 m (1 ft) was calculated. These results indicate that visibility reaches minimum acceptable limits at relatively low leakage levels.

The reason an unanticipated presence of smoke helped elevate workers' apprehensiveness is that miners tended to have certain predisposed beliefs about how the ventilation system should function and, consequently, where the smoke should be encountered under "normal" conditions. In a normal situation, fresh air comes into the mine via the intake air shaft, traverses the mine entries to the section, sweeps the faces, and then makes its way back to the upcast air shaft via the return aircourses. Ideally, air flow should occur with no air leakage across stoppings and overcasts, provided all ventilation devices are intact and mandoors are closed. However, minimal leakage is inevitable in any ventilation circuit regardless of how well stoppings and overcasts are sealed. Typically, a certain amount of air leakage will occur across mandoors, especially if they are left ajar. As calculations reported by Kissell and Litton [1992] show, smoke will make its way across ventilation devices into escapeways and other entries as a result of leakage.

About 37% of the miners who escaped the fires at the three mines apparently never considered the fact that air would leak across ventilation devices and introduce smoke into entries that they assumed should be clear. Surprisingly, some miners had misconceptions of how the smoke from the fires would travel. As a result, some groups of workers decided not to continue their escape in the smoke-filled intake escapeways or track entries and chose instead to move into the return aircourses, believing that the smoke there would be lighter or non-existent, since it would have to make its way to the faces before reaching the return entries. A continuous miner operator at Adelaide Mine, who was escaping with his crew from 1 Right section, elaborated on his crews' decision:

> Then if you have smoke in your intake, we were always taught to get into your return, and then keep checking until you see clear intake. So we got in our left return. There was no smoke because it hadn't reached up to the face and come back down the return.

At least one miner thought that by getting into the return, he and his crew would be safe, again because of a belief that any smoke in the intake must travel to the faces:

> We started in the intake escapeway, yeah. And whoever's decision it was, I don't know, because when we hit smoke, we decided it was time to get in the return because we figured all the smoke would have to go up to the unit or the face and come down behind us. So we're clear and out of all danger.

When miners encountered smoke in areas where they did not expect it, they began wondering how the smoke got there. A bolter operator described his thoughts:

> I think that was the thing that threw a lot of us off was when we came to the return, we hit the smoke on the haulage, we went over and we hit smoke in the belt entry, we got over into the return and it was still pretty clear. Because we went down 10 or more blocks, 15 blocks, whatever. That's when we starting hitting smoke [again]. Now, we got smoke in all, all the escapeways, you know. What is wrong?

In some cases, miners who became emotionally distressed assumed the worst when they encountered unexplained smoke. A utilityman quickly surmised that the fire had burned completely across the section when his crew hit smoke in the return:

> We were in the return by then and it was filled up with smoke and I knew we were in serious trouble then, we had a long way to go and we were already full of smoke...At that time, I couldn't get through my mind how we had smoke in the return escapeway that quick. I said, what did it do, burn all the way across and we don't have any way out now?

In fact, there were plausible explanations why smoke was being found unexpectedly in various locations at the three mines. As mentioned in an earlier chapter, a large quantity of air was being used to ventilate the 2 Northwest belt entry at Adelaide. Because this was a high-pressure entry, vast quantities of air quickly leaked across ventilation devices into adjacent intake and track entries, especially between the fire location and the mouth of 3 Left. As a result, significant amounts of smoke bled into these adjacent entries and eventually into the returns. This explains why the crews escaping encountered heavy smoke in all entries including the returns.

Several crews who escaped the fire at Brownfield Mine experienced similar situations, encountering smoke unexpectedly. Knowing that the beltline was on a separate split of intake air, miners escaping from the 5 South section decided to follow the belt, believing they would have clear air all the way out. When they encountered smoke in the belt entry, however, miners became concerned:

> We started down the belt because we figured the belt should have been neutral, really, but by the time we got there, the smoke was already on the belt line...we still can't figure out how the smoke got on the belt. Nobody—our boss can't figure out how the smoke got on the belt line. We should have been able to go down and get out the belt.

Misunderstandings about where smoke should be was not confined to rank-and-file miners. The mine inspector who escaped with the 4 South crew at Brownfield had a similar misconception. Knowing that smoke was already in the intake escapeway, the inspector checked the belt entry and found it to be clear. The section foreman, after conferring with the inspector, decided to take his crew down the beltline. All the while, the inspector thought the belt entry would be clear for the entire distance: "I really believed that the belt entry would be clear the entire way."

Some individuals, though, did think about why they were encountering smoke in certain locations and reasoned what was causing the problem. The mine inspector who escaped from 4 South at Brownfield Mine hypothesized later that a mandoor had to have been left open for there to be thick smoke in the belt entry:

> To this day we really didn't conclusively come up with an answer why that belt got contaminated. We checked the [stoppings]. I understand [stoppings] do leak somewhat but not to go from no smoke to thick heavy smoke in a matter of minutes. [Stoppings] don't leak that much. Someone left the doors open into that belt, also. I believe it.

At least one miner at Brownfield Mine was thinking clearly about why there was so much smoke in the belt entry. He was traveling with his buddies from 5 South:

> Thick smoke was in the belt lines before it was in the return...somebody goofed and opened something and left that air in. My opinion is that somebody opened the doors right across [4 South] ramp.

Finally, some miners at Cokedale Mine were perplexed by the way smoke "behaved" in the mine air courses, especially the return escapeways. Miners escaping from 8 Face Parallels were traveling in the return escapeway that led to Crystal air shaft. The workers noticed that there were points where the heavy smoke they were traveling in would suddenly lift and the air would become moderately clear. The miners might then travel several crosscuts in this clearer air until they encountered heavy smoke once again. A mechanic who was in the group escaping from 8 Face Parallels describes this occurrence:

> We headed out the return and we had gotten so far and it cleared a little bit, and we were kinda relieved, but then for some reason we hit the thick smoke again. It didn't clear completely but it looked like it was gonna clear, but then we went a few more blocks and it got real thick again. Why it was clear in that area I'm not really sure.

Because the smoke behaved in this manner, miners experienced a false sense of security when they reached the clearer air, only to find that the heavy smoke would return as they continued their egress. This undoubtedly helped to increase workers' anxiety as they escaped from the mine.

Discussion

Research on human behavior in smoke has shown that (1) people not familiar with escapeways tend to experience higher levels of emotional instability, and their ability to escape from a fire is severely reduced when the visibility falls below 13 m and (2) subjects familiar with escapeways experience relatively more problems with physiological effects of smoke, and their escape ability becomes hampered when the visibility falls below 4 m. Fire research data indicate that smoke reaches levels of untenability significantly earlier than it takes the fire to generate a toxic environment due to its product gases. It is only when the levels of smoke begin to totally obscure visibility that the toxicity of the combustion products begins to play a role in the question of escape and survivability.

Most of the miners who were caught inby the fires discussed here had never escaped through smoke. As a result, a number of workers experienced emotional instability that resulted from the need to cope with smoke in their escapeways. The psychological effects of smoke, in some instances, inhibited workers' ability to think clearly, make correct choices, and take proper action during their escape. In addition to suffering emotional upset during their escape, a number of miners also experienced some physiological effects of smoke, including smoke inhalation and eye irritation. In short, miners' ordeals in smoke when escaping mine fires confirm the findings of the research.

While underground miners must receive retraining annually on topics including mine ventilation, escapeways, emergency evacuation, and the use of SCSRs, it is evident that workers who escaped these three mine fires still were not adequately prepared to escape through smoke. In the future, mine operators may wish to consider offering smoke training to their workers as part of their annual retraining regime. Miners could don an SCSR training apparatus and then traverse a manmade network of corridors filled with nontoxic smoke. This type of training would allow miners to practice escaping through a smoke-filled environment, plus experience breathing through an SCSR.

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