Numerical modeling of the effect of underground mine fires on ambient conditions of refuge alternatives

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Federal regulations require the installation of refuge alternatives (RAs) in underground coal mines to provide a life-sustaining environment for miners trapped underground when escape is impossible due to fires and explosions. Given the regulatory requirement that the apparent temperature in a fully occupied RA shall not exceed 95 °F, NIOSH has been studying the thermal performance of refuge alternatives. However, no consideration has been given to the effect of fires on mine ambient conditions such as temperature and toxic gases near the refuge alternatives. The primary objective of this paper is to use mine fire simulation software to gain a better understanding of how a fire can affect the ambient conditions at RAs in an underground coal mine. A series of fire simulations with various fire locations and ventilation circuits in underground coal mines have been conducted. The ambient temperature and carbon monoxide levels near an RA for each scenario are carefully examined. Based on fire simulation studies, some general principles regarding improvements to ventilation circuit design and strategically locating RAs are also recommended in this paper.

Introduction

The Sago Mine disaster on January 2, 2006, in West Virginia demonstrated the need to provide mine refuge alternatives (RAs) for miners who are unable to escape the mine and are forced to take refuge during mine disasters or emergencies. Since 2006, in accordance with the Mine Improvement and New Emergency Response (MINER) Act of 2006, refuge alternatives are required in underground coal mines to provide a life-sustaining environment with breathable air for trapped miners for a 96-hour period when escape is impossible. Based on an accident and fatality data evaluation from 1900 through 2006, the Mine Safety and Health Administration (MSHA) estimates that 221 lives could have been saved over the 107-year period if refuge alternatives had been available [1]. The employment of refuge alternatives in the Australian metalliferous industry has saved trapped miners' lives in several mine fires with positive results, such as the fire incident at the Nickel Mine in Kambalda, Western Australia, which happened in March 2006, where nine miners took shelter in a portable refuge alternative for four hours after a loader fire [2].

Significant efforts have been made to investigate the utility, practicality, and survivability of refuge alternatives in underground coal mines [3]. Recently, considerable attention has been paid to understanding and solving the problems associated with heat and humidity buildup in refuge alternatives [4-9]. However, to the authors' best knowledge, little consideration has been paid to the effect of fires on mine ambient conditions such as temperature and toxic gases near refuge alternatives. The primary objective of this paper is to conduct mine fire simulations to gain a better understanding of how a fire can affect the ambient conditions at refuge alternatives in a generic underground coal mine, designated as the study mine hereafter. To achieve the goal, mine fire simulation software is used to obtain a dynamic representation of a mine fire's progress and track the spread of the combustion products and temperature throughout the ventilation system.

Mine layout and ventilation system

The study mine is a typical US longwall coal mine with two continuous miner development units and one longwall system. Exhaust ventilation is applied with the intake air entering the mine through an intake shaft and a belt slope, and the air exhausting via one main fan at the return shaft and one bleeder fan at the bleeder shaft. Eight-entry mains are developed with three intakes, one belt, and four returns. The longwall panel is 380 m (1250 ft.) wide and 5,180 m (17,000 ft) long. A three-entry chain pillar system is used to separate the panels. The nominal size of the entries and crosscuts is 2.5 m (8 ft) high and 5.0 m (17 ft) wide. The schematic of the mine ventilation system with necessary simplification is shown in Figure 1. Three colors (blue, red, and green) are used to illustrate the type of airways (intake-blue, return-red, and belt-green).

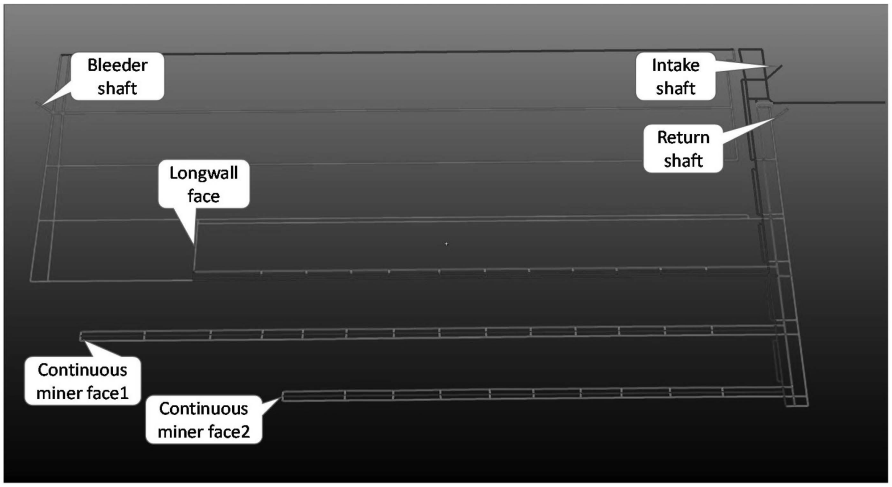

Figure 1: Mine ventilation schematic layout

Simulated fire scenarios

A total of 12 fire scenarios were simulated in the study to cover a broad range of underground coal mine fires. The fire locations for each scenario are displayed in Figure 2. Three of the fires are in the intake entry while the rest are in the belt entry. Belt entry fires have always been a great concern with respect to mine fire detection and prevention due to the combination of friction caused between the high-speed belt, poorly-aligned support structures, and flammable materials. Since 1980, belt fires have accounted for 15-20 percent of all fires reported to MSHA by coal mine operators [10]. For instance, a malfunction along the longwall belt drive and ignition of coal fines led to two miners' deaths at the Aracoma Alma Mine in West Virginia in 2016 [11]. The first three fires (Scenarios #1, #2, and #3) are at different locations along the "neutral" belt entry where the belt air is diverted directly to the return without ventilating the working sections.

Effective on June 1, 2004, all coal mine operators are allowed to apply for a variance to use belt air as intake air on working sections or in areas where mechanized mining equipment is being installed or removed in areas developed with three or more entries [12]. One of the safety concerns about the utilization of belt air is that the products of combustion could be carried to the working sections in mines and endanger the miners in the event of a belt fire. Scenarios #4, #5, and #6 are designed to represent three belt fires in the study mine using belt air at the face with the same fire locations as in Scenarios #1, #2, and #3, respectively.

Because refuge alternatives are all installed in the primary intake entry, it is apparent that the fire in the primary intake entry will impose an immediate and direct threat to the RAs. Scenarios #7, #8, and #9 are designed to simulate fires in the primary intake entry. These can be mine equipment fires. Scenario #7 has the fire in the main intake, Scenario #8 has the fire at the longwall panel primary intake 152 m (500 ft) from the mains, and the fire in Scenario #9 is 152 m (500 ft) upwind of the longwall refuge alternative.

The belt entry is required by law to be separated from the intake and return using stoppings or doors to prevent smoke and toxic gases from contaminating the adjacent intake entries and return entries. It is crucial for the purposes of mine fire rescue and evacuation to keep the primary escapeway free of smoke. A missing stopping had been blamed for the two miners' deaths in the Aracoma Alma Mine fire disaster, as the smoke breached the primary escapeway through a crosscut where a stopping was removed prior to the fire [11]. Scenarios #10, #11, and #12 are designed to simulate belt fires with a stopping failure. The fire is placed in the belt entry about 914 m (3,000 ft) from the longwall face. The stopping in the crosscut right next to the fire is removed. Scenario #10 maintains the normal ventilation where the air quantity in the belt entry is less than that in the primary intake. In the crosscut where the stopping is missing, the air flows from the intake into the belt entry. In Scenarios #11 and #12, the air is made to flow from the belt entry to the intake by adjusting the resistance between the belt entry and the intake. The airflow in the crosscut is 0.8 m^3/h (0.5 cfm) and 15.6 m^3/h (9.2 cfm) for Scenarios #11 and #12, respectively. Table 1 summarizes all of the simulated fire scenarios.

Table 1: List of simulated fire scenarios

Scenario	Fire location	Belt air
1	Main belt entry close to the portal	Neutral
2	Longwall belt entry close to the mains	Neutral
3	Longwall belt entry near the headgate	Neutral
4	Main belt entry close to the portal	Intake
5	Longwall belt entry close to the mains	Intake
6	Longwall belt entry near the headgate	Intake
7	Longwall intake close to the mains	Intake
8	Longwall panel intake close to the mains	Intake
9	Longwall panel intake close to the headgate	Intake
10	Longwall belt entry	Intake
11	Longwall belt entry	Intake
12	Longwall belt entry	Intake

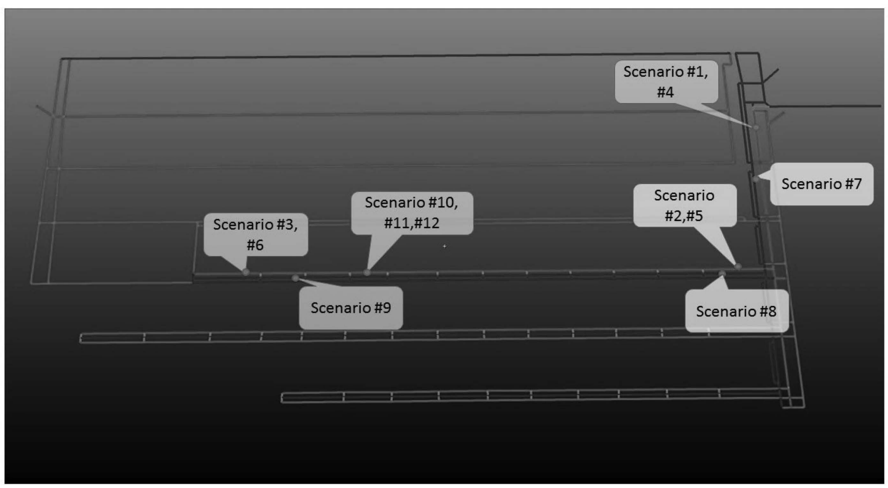

Figure 2: Fire locations within the mine ventilation schematic

Fire heat release rate

A mine fire is a complex physical and chemical phenomenon that strongly interacts with airflow in terms of oxygen supply. Therefore, fire research involves a number of disciplines including fluid mechanics, heat and mass transport, and chemical kinetics. The duration of a fire can be categorized into three stages: the growth stage, the fully developed stage, and the decay stage. In the growth stage, the fire may grow at a slow or a fast rate depending on the type of combustion, the type of fuel, the interaction with the surroundings, and the access to oxygen. The growth period of a fire could be very long, and the fire may die out before subsequent stages are reached [13]. At the fully developed stage, the heat released is at its greatest and the temperature near the fire zone is often very high. The decay stage starts as either the fuel or the oxygen depletes; the fire diminishes and thus the average temperature declines.

A fire can be completely described in terms of heat release rate (HRR), which is the primary variable that governs the combustible materials' contribution to the fire hazards and is also one of the most important parameters characterizing the energy intensity of a fire scenario. In this study, the different HRRs at three stages (as shown in Figure 3) are used to represent the development of the fire for all of the fire scenarios. The total fire duration is 2.5 hours with the peak HRR of 50 MW.

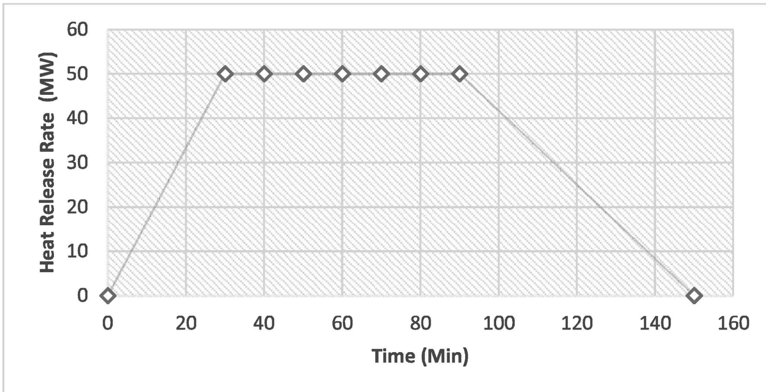

Figure 3: Heat release rate of the fire source

Locations of refuge alternatives

MSHA regulations (30 CFR Part 75.1506) require that refuge alternatives be provided within 305 m (1,000 ft) from the nearest working face and from locations where mechanized mining is being installed or removed except that for underground anthracite coal mines that have no electrical face equipment, refuge alternatives shall be provided if the nearest working face is greater than 610 m (2000 ft). The refuge alternatives are also required to be spaced within one-hour travel distance in outby areas where miners work. In this study mine, we mainly focus on the three refuge alternatives with one within 305 m (1000 ft) from the longwall section and two at continuous miner sections (as shown in Figure 4). The carbon monoxide level, temperature, and smoke at these three locations are comprehensively monitored during all the scenario simulations to investigate the effect of fires on the three refuge alternatives.

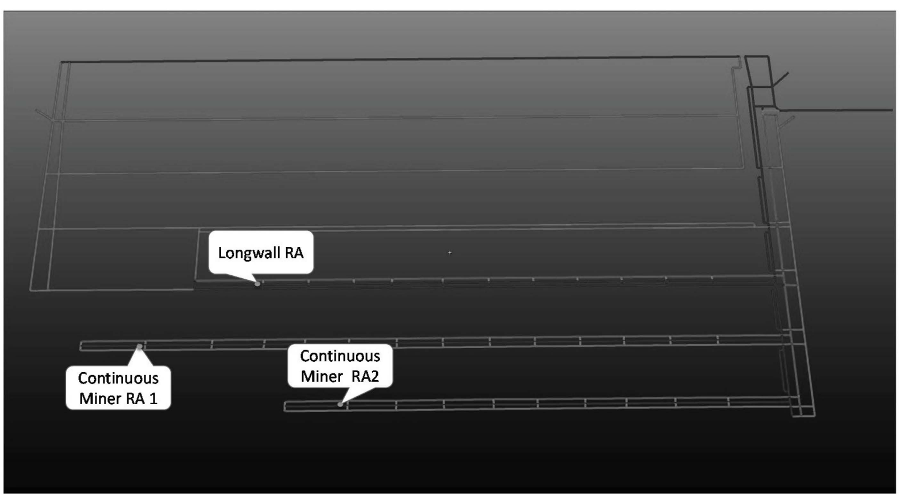

Figure 4: Refuge alternative locations within the mine ventilation schematic

Results and discussion

The scenarios #1, #2, and #3 simulated three fires at the different locations in the belt entry. The belt air in these three scenarios is separated from the intake and return and diverted directly to the return without being used by the working sections. The advantage of this ventilation plan is that it prevents the smoke and toxic gases produced by belt fires from spreading into the working sections where the miners work as the belt air is coursed away from the working faces. Scenario #1 assumed the fire was at about 60 m (200 ft) from the portal in the belt entry. As the airflow in the belt entry flowed out of the mine through the return shaft, the smoke and toxic gases produced by the belt fire were carried out of the mine instead of contaminating the longwall face and the two continuous miner faces. The contaminated area of the fire was only limited to the downwind area of the fire in the belt entry and the return shaft.

The temperature and the carbon monoxide level at the longwall refuge alternative and the two continuous miner refuge alternatives were closely monitored during the simulation. It was observed from the simulation that the carbon monoxide concentration reached 1.2% and the peak air temperature was as high as 426 ºC (800 F) adjacent to the fire source. The increase in temperature at the refuge alternatives was within 0.2 F. No carbon monoxide was detected at the refuge alternatives.

Scenarios #2 and #3 are the same as Scenario #1 for the fire source and ventilation plan but different for the fire locations. The fire in Scenario #2 was located 60 m (200 ft) from the mains in the longwall belt entry and the fire in Scenario #3 was 150 m (500 ft) outby the longwall face. Even though the fire in Scenario #3 was very close to the face and the refuge alternative in the primary intake, it was observed from the simulation that no smoke was spread to the face and the refuge alternative. The smoke was spreading with the airflow outward from the belt entry and eventually moved out of the mine from the return shaft. As the belt entry is isolated from the intake and the return with stoppings and doors, the only area contaminated by the fire is the belt entry downstream from the fire.

The simulation results from the above three fire scenarios demonstrate that the fire had no significant impact on the refuge alternatives located in the longwall panel and two continuous miner sections.

The ventilation plans were changed in Scenarios #4, #5, and #6 to use the belt air to ventilate the working sections. The fires in Scenarios #4, #5, and #6 are at the same corresponding locations as Scenarios #1, #2, and #3, respectively (as shown in Figure 2). For these three fire scenarios, the smoke and toxic gases generated by the fires were carried by the airflow all the way out through the longwall face to the returns. As the fire was in the main belt entry for scenario #4, the contaminated area included not only the longwall face, but also the two continuous miner sections. Very high levels of carbon monoxide from 2,200 ppm to 12,000 ppm was detected at all three working sections.

Given the fact that the fires in Scenario #5 and #6 are in the longwall panel, they did not impose any threat to the two continuous miner working sections. Table 2: Summary of carbon monoxide (CO) and temperature for scenarios 4, 5, and 6 displays the times for carbon monoxide to reach the longwall headgate after the occurrence of the fire, the peak carbon monoxide concentrations at the longwall headgate and the longwall face, and the temperature increases for these three fire scenarios. As shown, scenario #6 had the highest carbon monoxide concentration at both the headgate and the face.

Among these three simulated fires, the fire in Scenario #6 was the closest to the longwall face, and it resulted in about a 13ºC (55ºF) temperature increase in the air at the headgate, and smoke reached the headgate about 5 minutes after the fire started. In Scenarios #4 and #5, the temperatures at the headgate barely increased but the carbon monoxide levels were higher. In general, carbon monoxide is more dangerous than heat in a mine fire because of its toxicity and its wide and rapid spread with the airflow.

The main focus in these simulations was to investigate how the fires affect the refuge alternatives. Although working sections can be heavily contaminated by the fumes from belt fires when using belt air for face ventilation, the primary intakes where the refuge alternatives were located were free of smoke and toxic gases. One reason is that the larger air velocity in the primary intake created higher pressure than in the belt entry in these simulation cases, which overcame the fire-generated pressure to prevent leakage from the belt entry to the primary intake entry.

As in the first three simulating scenarios, neither carbon monoxide nor significant temperature increase was detected at any of the three refuge alternative locations in Scenarios #4, #5, and #6. It has to be noted that the belt entry usually has a higher resistance than the intake entry due to obstructions such as the belt itself, belt take-ups, etc. Air from belt entries will leak into the intake entries long before the belt entry is carrying more air than the intake entry [14].

Table 2: Summary of carbon monoxide (CO) and temperature for scenarios 4, 5, and 6

Fire Scenario	Time for CO to reach headgate (hr:min)	Peak CO at headgate (ppm)	Peak CO at longwall face (ppm)	Temp. increase (F)
4	1:22	2230	770	0.2
5	0:58	4400	1350	0.2
6	0:05	12300	3660	54.8

Given the fact that the fires of Scenarios #7, #8, and #9 are in the same entry as the refuge alternatives, they are anticipated to impact the refuge alternatives significantly compared to the previously discussed six fire scenarios. Scenario #7 had the fire in the main intake, resulting in all the working sections including the longwall face and the two continuous miner faces being contaminated by smoke and toxic gases.

Figure 5 displays the carbon monoxide concentration at each refuge alternative during this fire simulation. Carbon monoxide reached each refuge alternative about 30 minutes after the fire started, with a peak level of 1,600 ppm. The fire did not bring significant heat to the refuge alternatives as the temperature increase adjacent to the refuge alternatives was within 0.2 F. Both Scenarios #8 and #9 had the fire in the longwall panel; therefore, the refuge alternatives in the continuous miner sections were not affected by the fires, and only the longwall refuge alternative was affected. The times for the carbon monoxide to reach the longwall alternative refuge, the peak carbon monoxide concentration, and the temperature increase for Scenarios #7, #8, and #9 are summarized in Table 3.

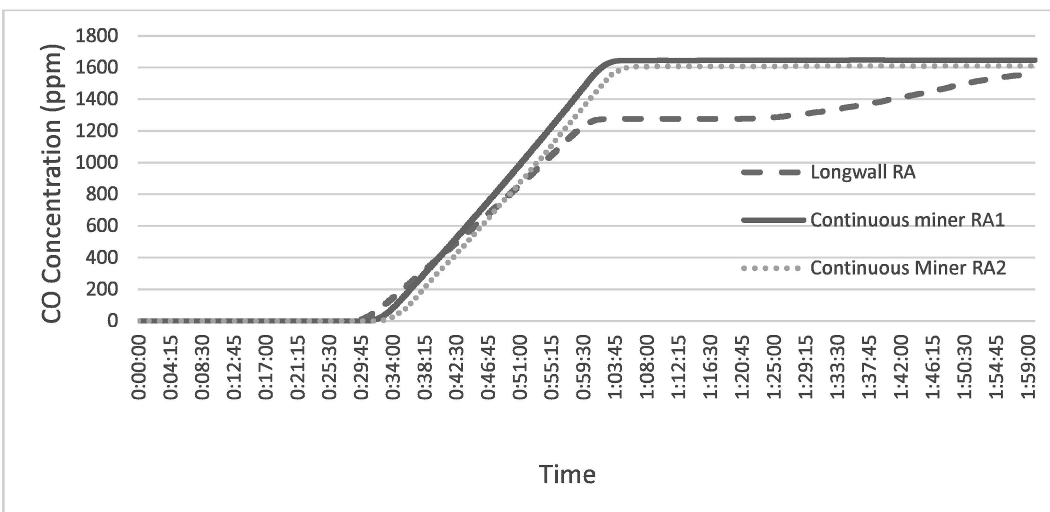

Figure 5: CO concentration at RAs for Scenario 7

Table 3: CO and temperature for scenarios 7, 8, and 9

Fire Scenario	Time for CO to reach headgate	Peak CO at RA (ppm)	Temp. increase (F)
7	0:29	1580	0.2
8	0:24	6440	0.7
9	0:05	9730	41.0

With a wide-open crosscut between the belt entry and the primary intake downwind of the fire, three different smoke spread phenomena were observed in Scenarios #10, #11, and #12. In scenario #10, the airflow in the intake was much larger than that in the belt entry. However, the difference in the resistances of the two entries and the “fire pressure” generated by the fire was not sufficient to make the airflow reverse in the crosscut. Therefore, there was no carbon monoxide detected at the longwall refuge alternative, and there was no significant temperature increase.

For Scenarios #11 and #12, the smoke and products of combustion flowed from the belt entry to the primary intake through the crosscut. This resulted in the longwall refuge alternative being impacted by the smoke and the toxic gases.

The carbon monoxide level at the longwall refuge alternative for Scenarios #11 and #12 is shown in Figure 6. Due to the larger air leakage rate from the belt entry to the intake entry in Scenario #12, the carbon monoxide reached the refuge alternative much earlier than in Scenario #11. The carbon monoxide concentration reached 2,000 ppm in Scenario #12.

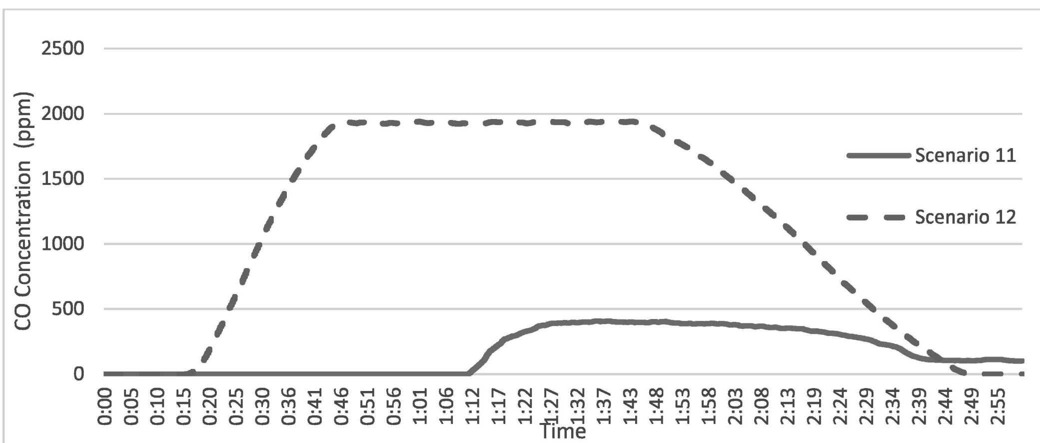

Figure 6: CO concentrations at the longwall RA for scenarios 11 and 12

Summary

The effect of mine fires on refuge alternatives in an underground coal mine has been studied using mine fire simulation software. The results of simulations can be summarized as follows:

The contamination of the refuge alternative’s locations by the smoke and the toxic gases was dominated by the route of the airflow. Under conditions in this study, refuge alternative locations were affected by smoke and toxic gases when the fire occurred in the primary intake entry or when there was a leakage flow from the belt entry to the primary intake entry in a belt fire. Maintaining a effective ventilation system is very crucial to preventing the spot where a refuge alternative locates from being contaminated by the products of combustions from a fire.

The carbon monoxide posed a more severe threat than the heat to the safety of miners inhabiting a refuge alternative in a mine fire. In the scenarios studied, when the fire was far located from the refuge alternatives, the heat from the fires did not have a significant impact on the refuge alternatives. However, the carbon monoxide could travel fast to the working sections and the refuge alternatives.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any company or product does not constitute endorsement by NIOSH.

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