Evaluation of deep-seated crib block fires and direct application fire suppression agents

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Abstract

Unlike other types of mining accidents, where an incident generally involves only a few workers, the danger of a mine fire extends to every person working in the underground environment. Mine fires can trap or kill those working underground by blocking avenues of escape and rapidly creating heat, asphyxiating gases and toxic fire products that can quickly spread throughout the mine. The National Institute for Occupational Safety and Health (NIOSH), in partnership with the Mine Safety and Health Administration (MSHA), is conducting research to test, evaluate and improve or modify coal mine fire-fighting strategies and methodologies through large-scale tests. Because wood is the second most abundant fuel available during a coal mine fire, it was decided that a series of large-scale wood crib fire tests was needed to measure the products of combustion and to observe the capability of commonly available direct application fire suppression equipment, namely, fire extinguishers, water and gas-enhanced foam. This paper discusses the wood crib fire tests, provides insight into the products of combustion and describes observations made during the application of the fire suppression agents.[1]

Background and introduction

When possible, during the early stages of a mine fire, common suppression agents such as fire extinguishers, water or foam are directly applied to contain or extinguish the fire. If the fire cannot be quickly brought under control, the mine is then evacuated to reduce the chance of injury or death due to exposure to the products of combustion. Once safe evacuation has been achieved, the entire mine or fire zone is sealed or contained to rob the fire of oxygen. Fire suppression and ultimate extinguishment then involves the remote injection of agents, including water, inert gas, gas-enhanced foam and possibly jet engine exhaust gases. Unfortunately some of these technologies are being used at mine fire sites without a fundamental knowledge of the technology and a comprehensive understanding of the proper application techniques.

In 2001, NIOSH and MSHA agreed to partner in research studies to develop new understandings of the characteristics of mine fires and the capabilities and limitations of mine fire suppression technologies. Since that time, it is believed that this partnership has served the mining industry well, as NIOSH and MSHA have worked together in the field at actual mine fire sites and in the laboratory and each has gained new insights into the science of mine fires and fire control and suppression technology. As a result of this partnership, research projects have been conducted and are ongoing in the areas of remote installation of mine seals and evaluation of remote suppression technologies (NIOSH, 2001; Trevits and Urosek, 2002; Mucho et al., 2005; Trevits et al., 2006a; Trevits et al., 2006b).

In late 2006, NIOSH initiated a new research project called "Remote Methods for Addressing Coal Mine Fires." The objective of this research project is to test, evaluate, improve or modify remote fire-fighting methodologies for coal mine fire control and suppression and to directly transfer these improvements and modifications to the coal mining industry. The research is focused on the completion of testing of remote mine seal technology (including the evaluation of rigid foam technology) and on the evaluation of fire-suppression technology. The work plan calls for large-scale, controlled deep-seated (firmly established) coal fire tests to be conducted underground

[1] The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH.

in the NIOSH Lake Lynn Experimental Mine. A series of large-scale, deep-seated wood crib fire tests was added to the work plan because the use of wood is so prevalent in underground coal mines. It was thought that the wood crib fire tests would yield significant information about the combustion products of wood components that are typically consumed in a mine fire and could offer a platform for evaluating the capability of directly applied fire suppression technology.

Previous research was conducted by the U.S. Bureau of Mines on wood crib fires in an intermediate-scale fire tunnel (Trevits, 2006b). The previous work involved various Douglas fir crib block configurations and generated critically important information on carbon monoxide (CO) and carbon dioxide (CO_2) gas concentrations, smoke particle characteristics and heat release rates. The present study serves to expand and supplement the previous work using large-scale mixed wood species crib block fire tests.

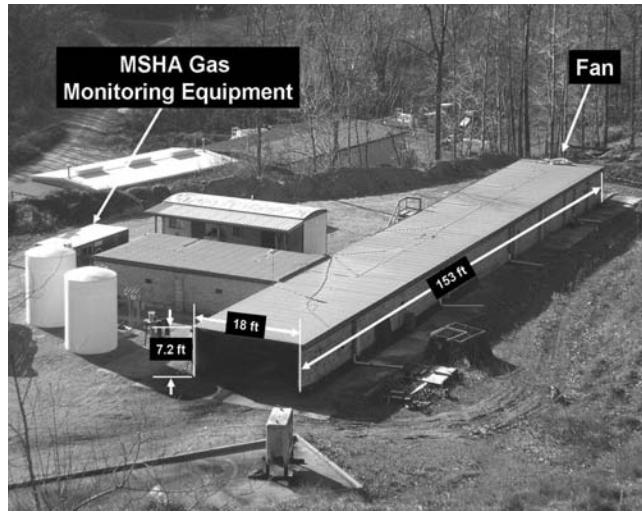

Figure 1 — Fire suppression facility.

Objective and approach

The objective of this study was to conduct a series of large-scale, deep-seated, wood crib fire tests to measure the various combustion products and to observe the capability of commonly available direct application fire suppression technology, namely, fire extinguishers and water and gas-enhanced foam.

Fire suppression facility

The crib block fire tests were conducted at the Fire Suppression Facility (FSF), and MSHA provided supplemental gas monitoring equipment for the tests along with technical experts to operate the equipment. The FSF is part of the NIOSH Lake Lynn Laboratory (LLL), which is located approximately 100 km (60 miles) southeast of Pittsburgh, Pennsylvania. The LLL is a world-class, highly sophisticated surface and underground facility where large-scale explosion trials and mine fire research is conducted (Egan and Litton, 1986).

The FSF was configured to simulate a 46-m- (150-ft-) long mine entry. The interior height of the simulated mine is 2.2 m (7.2 ft) and the width is 2.4 m (8 ft). The roof of the simulated mine is made of corrugated steel bridge planks, the ribs are made of 203-mm- (8-in.-) thick mortared solid concrete blocks, and the floor is made of reinforced concrete. The interior roof is covered with a 50.8-mm- (2-in.-) thick layer of Fendolite M-II® (a specialized fire resistant mixture of vermiculite and Portland cement) and a 25.4-mm- (1-in.-) thick layer of Fendolite M-II® has been placed on the ribs.[2] For ventilation, a 1.8-m- (6-ft-) diameter variable-speed axivane fan (equipped with a pneumatic controller to adjust fan blade pitch) has been installed at one end of the simulated mine. The fan can provide blowing sustained airflow up to about 5.84 m/s (1,150 fpm) over the cross-section of the entry. Two doors, which permit access to the inside of the FSF, are located about 14 m (47 ft) from the fan. Figure 1 shows the exterior of the FSF.

The FSF is equipped with an array of chromel-alumel thermocouples (type-K) projecting 30 mm (1.2 in.) down from the mine roof. The thermocouples are spaced at 3 m (10 ft) intervals starting about 3 m (10 ft) from the fan leading along the centerline to the end of the simulated entry. The thermocouples are connected via a wire network to a computer-based data-acquisition system. During the crib fire tests, data were collected at 10-second intervals and radiation corrections were not made in the temperature data. Video images of the tests were recorded using a camera that was positioned on the one side of the mine entry about 6.4 m (21 ft) upwind from the crib block sets.

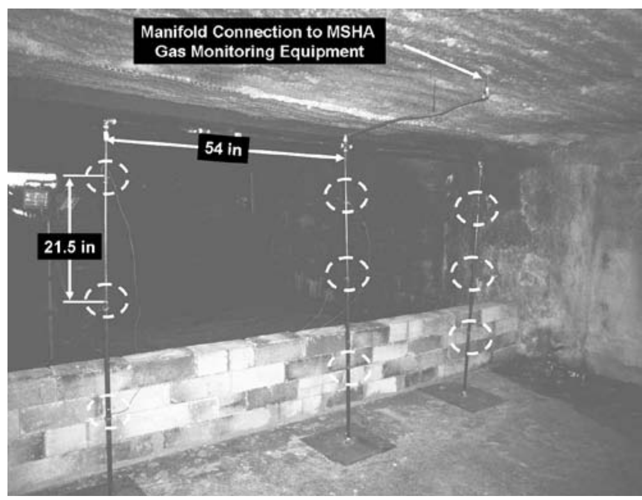

Figure 2 — Layout of a gas-monitoring array. (Circled areas show gas monitoring points and thermocouples.)

The components of the fire gases were measured using three gas-monitoring arrays. The first was a nine-point array located 6.46 m (21.2 ft) from the trailing edge of the crib block sets. The array consisted of an interconnected network of 12.7-mm- (1/2-in.-) diameter black iron pipe set across the width of the mine entry. A total of nine 3.175-mm- (1/8-in.-) diameter holes were drilled into vertical sections of the pipe to sample the fire gases. The holes in the pipe were spaced equally apart from the roof-to-floor and across the width of the entry (Fig. 2). A thermocouple was also positioned at each gas sampling point to measure the temperature of the fire gases. The gases collected at each sample point were mixed together in a manifold that penetrated the FSF roof. The manifold was connected to a Tygon® tubing line that led to the MSHA gas monitoring truck. The second gas-sampling array was configured in the same manner as the first and was located 29.1 m (95.5 ft) from the trailing edge of the crib block sets. The third gas-sampling array was positioned near the second gas-sampling array and consisted of four 3.175 mm (1/8 in.) holes drilled into 25.4-

[2] Reference to product or trade names does not imply endorsement by NIOSH and MSHA.

Table 1 — Laboratory data from crib block samples.

	Average			Standard deviation		
Sample condition:	**AR**	**Dry**	**DAF**	**AR**	**Dry**	**DAF**
Moisture, %	25.52	–	–	7.11	–	–
Ultimate analysis, %						
Hydrogen	6.68	5.11	5.13	0.30	0.21	0.21
Carbon	37.55	50.49	50.72	3.40	0.47	0.45
Nitrogen	0.09	0.11	0.11	0.01	0.02	0.02
Sulfur	0.06	0.09	0.09	0.03	0.03	0.03
Oxygen	55.29	43.76	43.95	3.12	0.29	0.31
Ash	0.33	0.45	–	0.12	0.16	–
Heating value (Btu/lb)	6,424	8,652	8,691	470	259	265

AR = as received
DAF = dry ash-free

mm- (1-in.-) diameter black iron pipe (spaced equally from the roof-to-floor). The pipe was positioned vertically at the centerline of the entry and was connected to a line that led to a set of NIOSH infrared gas analyzers. The gas analyzers measured O_2, CO and CO_2 gas concentrations and the resultant data was collected at 10-second intervals and recorded by a computer-based data-acquisition system.

In the MSHA gas monitoring truck, the gas samples were analyzed using a combination of infrared and electrochemical gas analyzers (the gases analyzed included O_2, CO, CO_2 and methane (CH_4)). Throughout each test, the data from the MSHA gas analyzers were collected at 2-minute intervals and were recorded in a computer database. In addition, gas samples were collected periodically over 3- to 4-minute intervals from the first gas-sampling array and were analyzed using gas chromatography. The analysis of each of the gas samples by the chromatograph took about 10 minutes to complete. Therefore, during each test, a sample was collected and analyzed approximately every 13 to 15 minutes. The gases analyzed included H_2, O_2, CO, CO_2, CH_4, acetylene (C_2H_2), ethylene (C_2H_4) and ethane (C_2H_6). The gas chromatography results were verified by back-up gas bag samples that were periodically collected from the same sample point and analyzed using a different chromatograph at a MSHA laboratory. The NIOSH and MSHA gas analyzers and the MSHA gas chromatograph were calibrated before each test (the calibration standard was 5 ppm H_2, C_2H_2 and C_2H_4 and 10 ppm C_2H_6). After each test, the MSHA gas analyzers were checked with fresh air to determine instrument drift.

Composition of the crib blocks

The crib blocks were comprised of a variety of mixed hardwood species, including beech, cherry, maple, white oak, red oak and poplar. To insure that the crib block sets would burn evenly and produce a more intense fire, the crib block sets were composed of an even mix of older blocks (about 6 to 8 months old) that had been stored underground at the LLL and newer blocks that were delivered to the LLL about two months prior to the tests. All blocks were obtained from the same vendor, and the wood was milled from two days to one month before shipment to the NIOSH. Ten crib blocks (five newer and five older blocks) were randomly collected and 76-mm (3-in.) cube-shaped samples of wood were cut from each of the selected crib blocks. The samples were sent to an independent testing laboratory for moisture, ultimate analysis and heating value determinations. The averaged laboratory data from the 10 samples analyzed are shown in Table 1.

From Table 1 it can be observed that the wood contained an average of about 25.5% water. This average moisture value and the associated high standard deviation was expected because, as discussed above, half of the crib blocks were "green," and these blocks did not have much time to lose moisture prior to the tests. Fuel moisture is an important factor with regard to the crib fire tests. If high moisture content wood is burned, the resulting fire will take longer to reach ignition temperature, the fire will be less intense because much heat energy will be used to convert the moisture to steam, and the fire will produce more particulates and smoke. On the other hand, if low moisture-content wood is burned, the resulting fire reaches the ignition temperature faster, is more intense and produces less smoke and particulates. Finally, because the samples of the wood were a combination of newer and older samples, the variation in the moisture content of the wood caused a variation in the heating value from an average of about 14.9 MJ/kg (6,400 Btu/lb), with a 1.1 MJ/kg (470 Btu/lb) standard deviation.

Crib block set geometry

Table 2 provides information about the crib blocks used in this study. Each crib block set was constructed on a foundation consisting of eight solid concrete blocks, with each concrete block measuring 152 mm high, 203 mm wide and 406 mm long (6 in. high, 8 in. wide and 16 in. long). A total of 34 crib blocks were stacked vertically to build each crib set (17 of the older crib blocks and 17 of the newer crib blocks). Each row of blocks was oriented perpendicular to the adjacent row. The bottom row contained four crib blocks (two newer blocks on the outside and two older blocks on the inside) oriented with the 152 mm (6 in.) side facing down, the next row contained four crib blocks (two newer blocks on the inside and two older blocks on the outside) oriented with the 152 mm (6 in.) side facing down. The next row contained three crib blocks (two older blocks on the outside and one newer block on the inside) oriented with the 152 mm (6 in.) side facing down. The next row contained three crib blocks (two newer blocks on the outside and one older block on the inside) oriented with the 152 mm (6-in.) facing down. The remaining rows contained two crib blocks each, alternating between the new and older blocks in each row with the 127 mm (5 in.) side facing down. The final row of blocks was adjusted with the 127 or 152 mm (5 or 6 in.) side facing down, depending on the relative closeness of the mine roof.

The crib blocks were secured to the roof with wedges as needed. To insure the maximum stability of each crib set, for the longest period of time, each crib set was wrapped with poultry fencing that was affixed to the wood with staples. Figure 3 shows the typical crib block set-up prior to a test.

FSF test set-up

The layout of the FSF for the crib block tests is shown in Fig. 4. The crib blocks were located 15.8 m (52 ft) from the fan and 10.4 m (34 ft) from a simulated conveyor structure in the FSF. The crib block sets were placed 0.45 m (1.5 ft) apart and were positioned near the center of the entry. As mentioned above, the crib block sets were constructed on solid concrete blocks and located in the middle of the blocks was an impinged natural gas burner that was equipped with 60 stainless steel jets (with a rated heat output of 44 to 114 kW). The burners were set on the simulated mine floor with the jets positioned about 50 mm (2 in.) below first row of crib blocks. Natural gas was used instead of an accelerant (e.g., diesel fuel) to assist in starting the fires, because it was more readily consumed by the fire and left no residue that could have altered the wood fire combustion products. A series of preliminary experiments showed that the natural gas burners would need to operate for about 50 minutes to ensure that the crib fires would burn without the need to relight the burners.

Prior to igniting the fires, the ventilation flow rate was measured in front of the crib block sets, at the first gas sampling array and at the location of the second and third gas-sampling array. At each location, the ventilation airflow rates were measured at nine points in the cross-sectional area of the mine entry and an average flow rate was determined. Table 3 shows the ventilation airflow rate data for the tests.

Crib block fire tests

The crib fire tests were designed so that four sets of crib blocks would be burning simultaneously as the combustion products were measured. As the tests were being conducted, the estimated heat release rate of the fire was calculated from the gas data and the intensity of the fire (and smoke rollback) was monitored remotely using the video camera. The estimated heat release rate or estimated energy output of the fire was determined using the amount of CO and CO_2 in the combustion product air stream, the rate of consumed oxygen and the relative increase in temperature. The methodology used for making the estimated heat-release rate calculations is defined in detail in Smith et al. (1995). The heat-release rate estimations were made using the data collected by the MSHA infrared and electrochemical equipment at gas sample Arrays 1 and 2 (CO, CO_2 and O_2) and the NIOSH thermocouple data collected at the same locations. The final estimate of the heat release rate was calculated by averaging the estimated heat-release rates from the amount of CO and CO_2 in the combustion product air stream and the rate of consumed oxygen. The estimated heat-release rate that was calculated using the temperature data was inordinately low due to significant heat loss to the FSF. As a result, these values were not used in overall heat-release rate determinations.

In this study, a total of five tests were conducted, including two crib fire control tests. The first control test involved crib block sets that were stacked in a normal manner, and the second control test involved crib block sets that were normally stacked and enclosed in a steel framework. The framework was designed to make the crib block sets stand upright for a maximum period of time. The control tests were designed to serve as the base case for the extinguishment tests and the fires were permitted to burn until the estimated heat release rate declined significantly. Three crib set fire tests with extinguishing agents (fire extinguishers, water and gas-enhanced foam) were also conducted. These fires were permitted to burn until they were emitting a stable and steady amount of heat (as determined by the heat release-rate calculations) at a consistent level of intensity with minimal smoke rollback (as determined by the video camera) before the fire-extinguishing agents were applied. If a crib block set fell prior to application of the fire suppression material, an interval of time was needed to allow the fire to stabilize before the fire suppression material was applied. In this manner, the effect of applying the extinguishing agents to the fire could be readily observed in

Table 2 — Crib block information.

Parameter	Data
Block height, in.	5
Block width, in.	6
Block length, in.	30
Average block weight, lbs (S.D., lbs)	27.2 (3.05)
Number of blocks used per crib block set	34
Number of crib block sets used per test	4
Number of crib blocks used per test	136

S.D. = Standard deviation

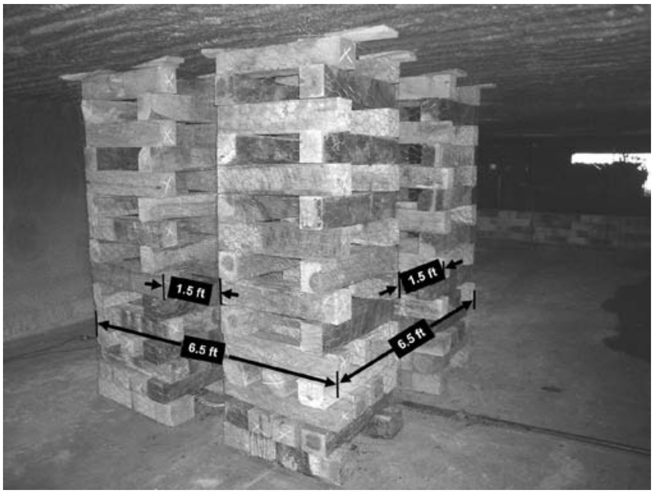

Figure 3 — Typical crib block set-up prior to a test.

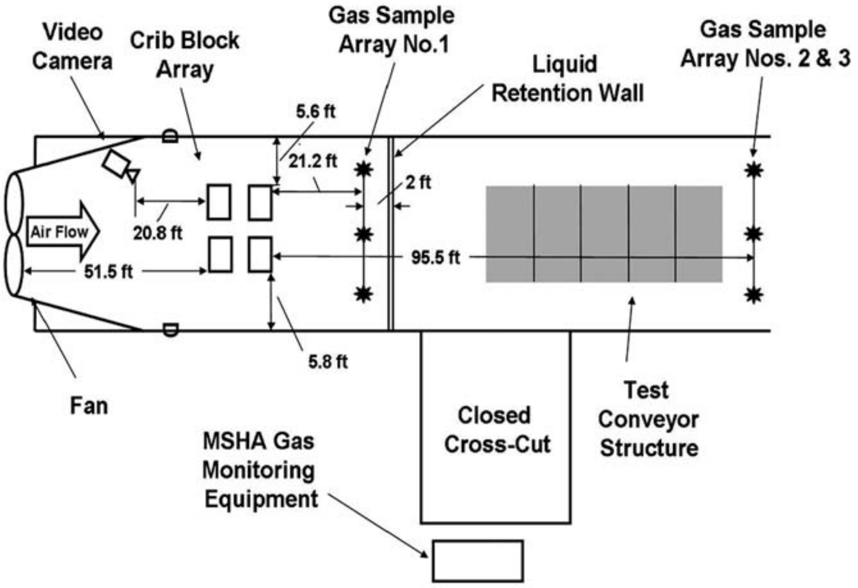

Figure 4 — FSF typical set-up for a crib fire test.

Table 3 — Average ventilation flow rate information for the crib fire tests.

Description	Test mumber 1	2	3	4	5
In front of the crib block sets, ft/min	290	300	395	310	300
(Changed rate, ft/min)[1]				(340)[1]	
MSHA Gas sample array No. 1 - air velocity, ft/min	330	300	280	295	270
(Changed rate, ft/min)[1]				(320)[1]	
MSHA Gas sample array No. 2 - air velocity, m/sec	315	320	285	310	280
(Changed rate, ft/min)[1]				(330)[1]	
NIOSH Gas sample array - air velocity, ft/min	315	315	285	310	280
(Changed rate, ft/min)[1]				(330)[1]	

[1]Severe smoke rollback required an increase in the flow rate.

Figure 5 — Control test – Burning crib block sets.

the heat-release rate data would not be perturbed by dramatic variations caused by changes in the geometry of the blocks or intensity of the fire. Below are summaries of each test.

Crib block Tests 1 and 2 (control tests). In Test 1, after the gas supply was turned off it was observed that the back set of blocks were burning more intensely than the front set of blocks, most likely because they were sheltered from the ventilation air flow by the front set of crib blocks. Although the fire grew vertically through each crib block set, the ventilation air currents caused the fire to burn more intensely towards the backside (downwind side) of each crib block set (Fig. 5). It was determined that this burning condition would most likely cause the crib sets to topple over rather than collapse vertically. The fire burned unremarkably until 94 minutes into the test, when the rear left crib block set fell down. About 18 minutes later (112 minutes into the test) the rear right crib block set fell down. About 30 minutes later (142 minutes into the test) the front left crib block set fell down into the debris of the left rear crib block set and about 20 minutes later (162 minutes into the test) the front right crib block set fell down into the debris of the rear right crib block set. Each time a crib block set fell, the intensity of the fire increased for a short period of time.

As discussed above, Test 2 was designed to serve as the alternate control base case for the extinguishment tests and involved four crib block sets that were enclosed in a steel framework. The fire burned unremarkably until 123 minutes into the test, when the fire in the left rear crib set intensified dramatically with flames reaching the simulated mine roof and subsequently engulfing the right rear crib set. Some smoke rollback was observed, extending towards the video camera location. This event lasted for about five minutes and then the fire reduced to about the same level observed before the event occurred. At about 147 minutes into the test, the front left crib set fell into and toppled the rear left crib set. The fire then burned more intensely, and about two minutes later the rear right crib set fell (about 149 minutes of elapsed time). The fire continued to burn and eventually reduced in size over the next 20 minutes. At about 203 minutes into the test, the right front crib set fell, and the fire again intensified. No other significant events occurred.

A plot of the estimated heat release rate and the products of combustion for both tests are shown in Figs. 6a, 6b and 6c. From the figures, it appears that Test 1 emitted a larger amount of heat and produced a larger amount of CO_2 and less CO, suggesting more complete combustion of the crib blocks than in Test 2. Also, the gas chromatograph data (Fig. 6c) shows that H_2, C_2H_2, C_2H_4 and C_2H_6 gases were observed in the combustion product air stream during both tests, and these gases are most likely the products of incomplete combustion and pyrolysis of the wood. During Test 1, the concentration of hydrogen and the hydrocarbon gases appeared to follow the general trend of the CO gas concentration. This same relationship was observed in the H_2, C_2H_2, C_2H_4 and C_2H_6 gas concentrations measured during Test 2.

Each time a crib block set fell, the geometry of the wood changed, and the fire burned more intensely for a period of time. The change in the intensity of the fire is reflected as an increase in the estimated heat-release rate immediately following one of these events along with the associated increase in the products of combustion. The increase in fire intensity is most likely due to the close proximity of the fallen burning crib blocks and the associated heat build-up.

As planned during Test 2, the steel framework did indeed hold the crib sets upright for about 50 minutes longer than the unconfined crib block sets in Test 1. It was decided that framework system, though useful for keeping the crib sets erect, did not substantially extend the life of the fire tests and represented a considerable deviation from typical crib block configuration used in a coal mine setting. The steel framework system was, therefore, not used in any of the subsequent extinguishment tests.

Crib block test (water suppression agent applied). This test was designed to observe the effects of water application on a deep-seated crib set fire because water is the most commonly available fire suppression technology. Water is an effective suppression and extinguishing agent because it cools the wood surfaces and therefore reduces rate of pyrolysis. For this test, water was supplied from a fire truck to a fire hose that was equipped with an industrial plastic fog nozzle (the type that is typically available in a coal mine) that was adjusted to form stream flow. A total of 9.07 m^3 (2,400 gal) of water was available from the truck for the test. Water was supplied through the fire hose to the nozzle at a rate of 4.7 L/s (75 gpm) at 690 kPa (100 psi).

The test was initiated in the same manner as the control tests. At about 41 minutes into the test, the fire grew to the mid-height in the right and left rear crib block sets, and over the next four minutes there were periods of increased intensity with smoke rollback. At 46 minutes into the test, the right rear crib block set was burning intensely at the top with flame spread across the roof towards the rib areas. This condition continued for about two minutes and eventually included all crib block sets, with periods of heavy smoke rollback. At 49 minutes into the test, the fire had reduced in size and the smoke rollback problem had diminished. The fire then burned without any remarkable events until about 70 minutes into the test, when a small increase in intensity was observed in the lower portions of the front left and rear right crib block sets. This event lasted for about two minutes and then the fire reduced to about the same level observed before the event occurred. It was decided to apply the water extinguishing agent at about 76 minutes into the test, because the fire had reached a steady-state burning rate.

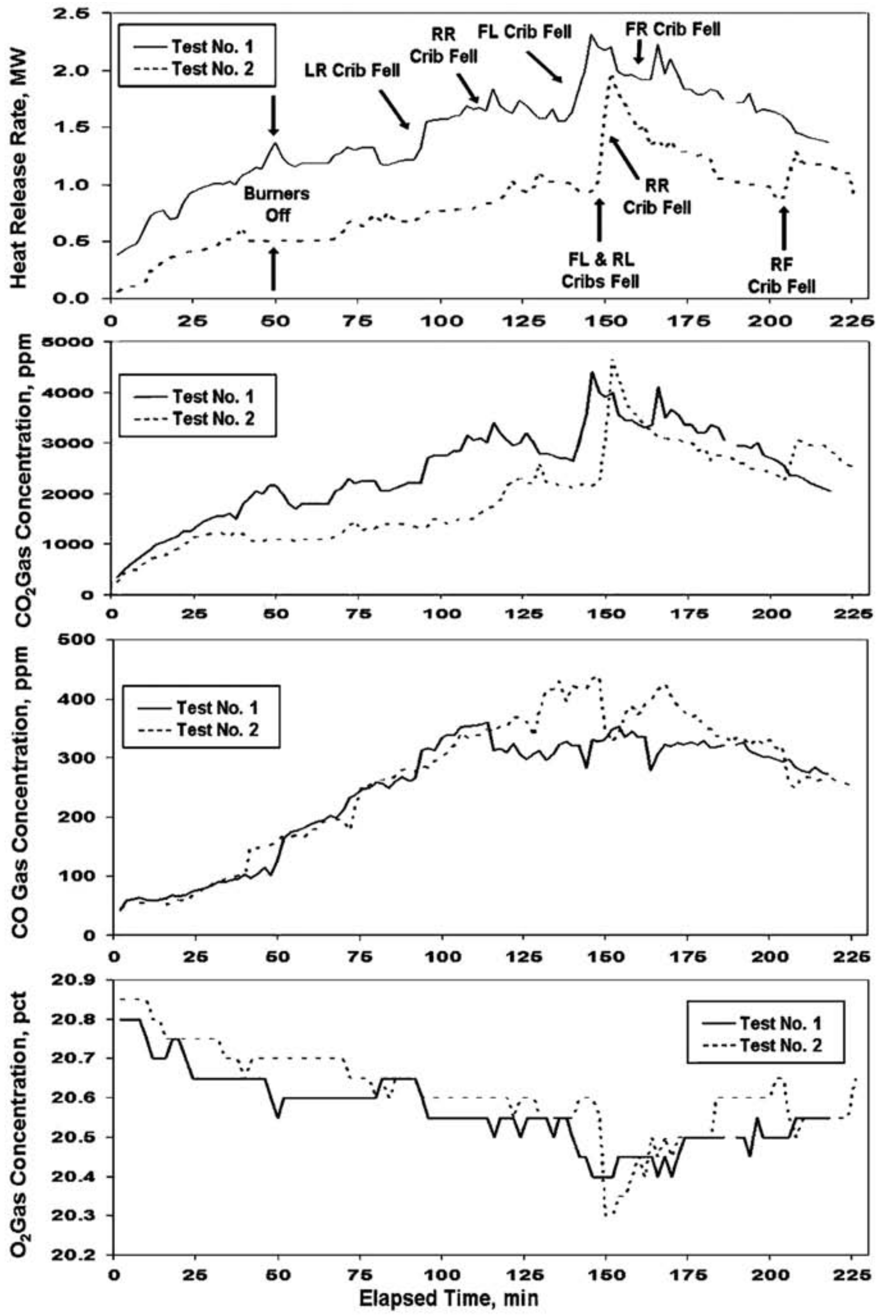

Figure 6a — Plot of estimated heat release rate and products of combustion for crib block Tests 1 and 2.

The individuals selected to apply the water to the fire were NIOSH technicians who had previously served as coal miners and had training and experience in the use of a fire hose. The technicians were instructed to apply the water until they observed that the fire had been extinguished. For personal safety reasons, the technicians were also instructed not to progress past a line that had been drawn on the entry floor (perpendicular to the trend of the entry) about 457 mm (18 in.) upwind from the leading edge of the crib block sets. This location was selected because it would keep the technicians out of the smoke and away from the heat of the fire. Water was applied to the fire for about four minutes when the technicians decided the fire had been extinguished, and a total of 1,135 L (300 gal) of water was used (Fig. 7). Observations of the wood showed that the horizontal surfaces appeared to be wet and water was observed to be actively dripping from the vertical surfaces. About four minutes after the water application was completed, hot spots (glowing embers) were observed in the rear left and rear right crib block sets. At about 52 minutes after the water application was stopped, small flames were observed in the rear left crib block set. The embers and flames eventually self-extinguished and no other events were observed.

Figures 8a and 8b are plots of the estimated heat release rate and the products of combustion for this test. As observed in the control tests, the fire showed an increase in heat output and CO_2 production during the intense burning event or when the crib block sets shifted or fell. CO production increased at a steady rate with only slight changes when the fire intensified or when the crib block set shifted or fell. As expected, the heat output of the fire and the production of combustion gases declined dramatically as the water was applied (refer to Figs. 8a and 8b). As observed in the controls tests, the fire also pro-

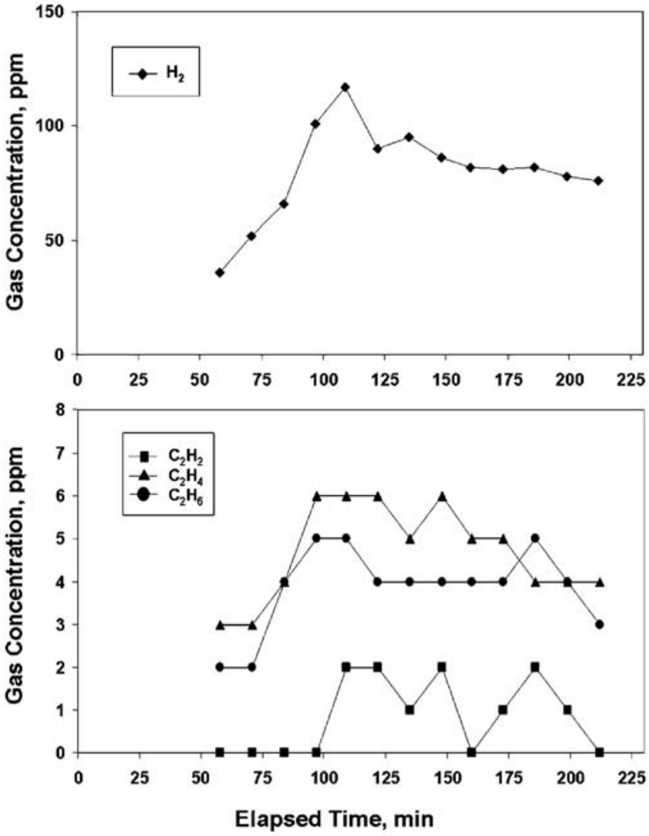

Figure 6b — Gas chromatograph data for Test 1.

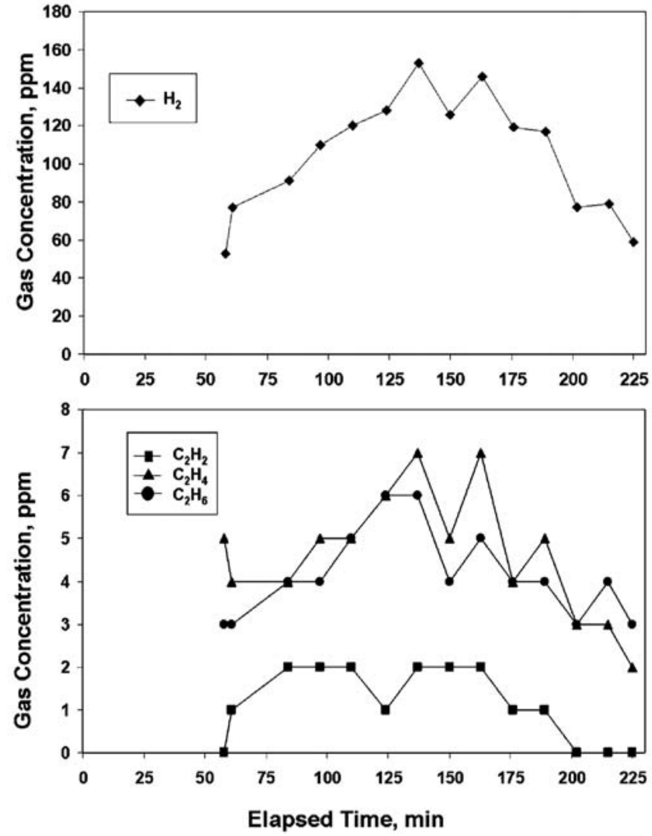

Figure 6c — Gas chromatograph data for Test 2.

Figure 7 — Use of fire hose during crib block fire Test 3.

duced H_2, C_2H_2, C_2H_4 and C_2H_6 gases, which are considered to be the products of incomplete combustion and pyrolysis of the wood. Unfortunately, because this test was of a short duration and only a very limited set of gas chromatograph data was collected during this test, it is therefore difficult to make comparisons with the other gas species.

Crib block Test 4 (gas-enhanced foam suppression agent applied). This test was designed to observe the effects of a portable gas-enhanced foam fire suppression technology. Compressed air or nitrogen gas, when added to a mixture of foam concentrate and water, creates foam that can expand up to twenty times the original liquid volume. Foam addresses a fire condition through evaporation of contained water and through cooling by energy removal. It serves to blanket the combusting material and isolate it from oxygen. As the foam collapses, water is released and the temperature of the water increases by absorbing heat and eventually turns the water into steam. Water is released from foam either during bubble rupture and because this process takes time, foam can act as a water reservoir, releasing water at a rate that allows absorption into the fuel, rather than running off the surface (The Snuffer Corporation, 2006). If nitrogen gas is used to make the bubbles, then the resulting foam can serve to remove two components of the fire tetrahedron by robbing the fire of heat and by removing or displacing oxygen.

The system used was a Sentinel 120RS unit supplied by USF Equipment and Services (a research partner in this test). The Sentinel 120RS is a self-contained fire-fighting system that uses the patented Hellfighter® mixing chamber to create foam (USF Equipment and Services, 2006). The system used was capable of producing 9.07 m^3 (2,400 gal) of gas enhanced foam using a mixture of water, a small amount of Mine Fire Fighting Foam® (MFFF) concentrate and nitrogen gas (Fig. 9). The system can discharge up to 18.9 L/s (300 gpm) of gas-enhanced foam. Prior to the entry into the FSF, the NIOSH technicians were instructed on the proper use of the Sentinel unit and application of the foam product on the fire. As in the previous test, the technicians were instructed to apply the gas-enhanced foam until they observed that the fire had been extinguished.

The test was initiated in the same manner as the previous tests. At 44 minutes into the test, the fire began to grow and

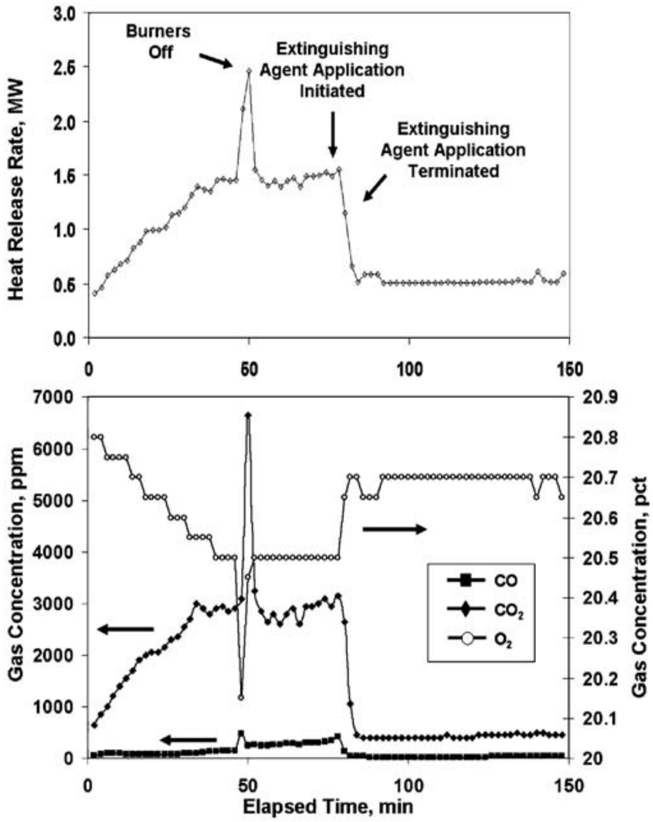

Figure 8a — Plot of estimated heat release rate and products of combustion for crib block Test 3.

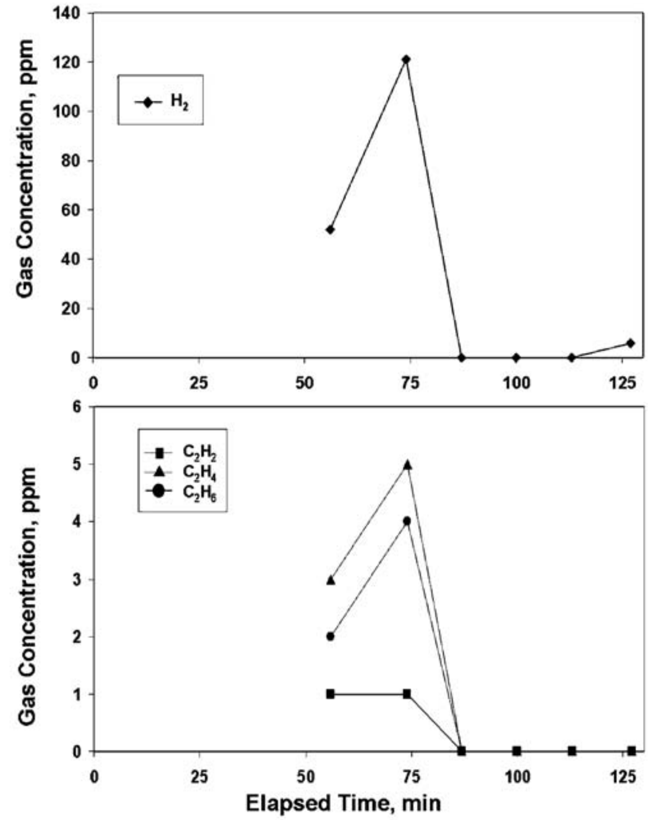

Figure 8b — Gas chromatograph data for Test 3.

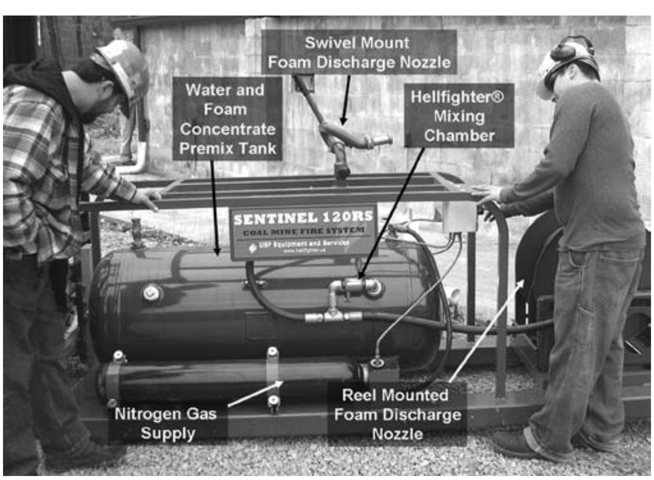

Figure 9 — USF Sentinel® unit used during crib block fire Test 4.

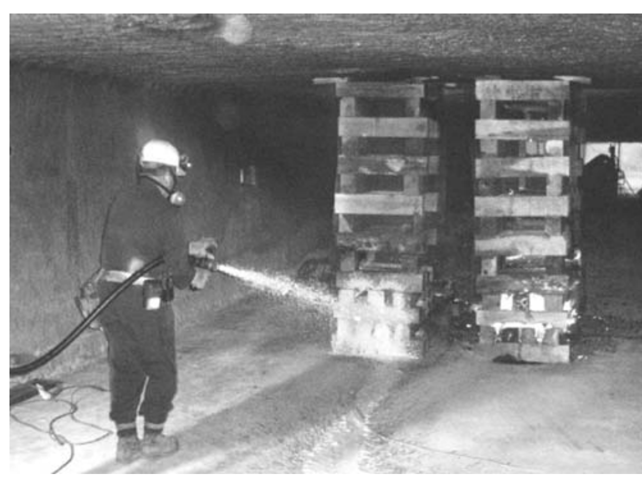

Figure 10 — Use of gas-enhanced foam during crib block Test 4.

within three minutes, the fire had substantially increased and was burning at the top of both the right and left rear crib sets with periods of severe smoke rollback. At 50 minutes into the test, the burners were turned off and the fire intensity subsided; however, the smoke rollback problem continued. At about 68 minutes into the test, the fire intensified followed by active burning at the top of the right and left rear rib block sets. This event continued for about four minutes with periods of heavy smoke rollback. At about 71 minutes into the test, the smoke rollback problem became so intense that it was decided to increase the ventilation flow rate (refer to Table 3). Within a few minutes the increase in the ventilation rate cleared the smoke rollback problem, and it was decided to let the fire stabilize to the new ventilation conditions before attempting to extinguish the fire. At about 80 minutes into the test, the rear left crib block set fell followed by a brief increase in fire intensity.

Gas-enhanced foam application began 103 minutes into the test, and about 1 minute later, the right rear crib block set fell down (Fig. 10). Foam application continued for about 8 minutes when the technicians decided that the fire had been extinguished. A total of 9.07 m^3 (2,400 gals) of gas-enhanced foam (the entire capacity of the system) was used. At about 40 minutes

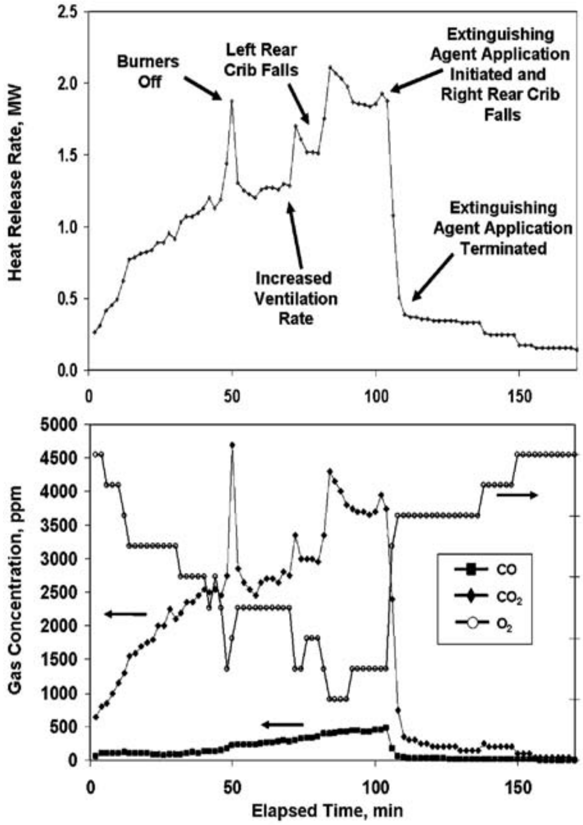

Figure 11a — Plot of estimated heat release rate and products of combustion for crib block Test 4.

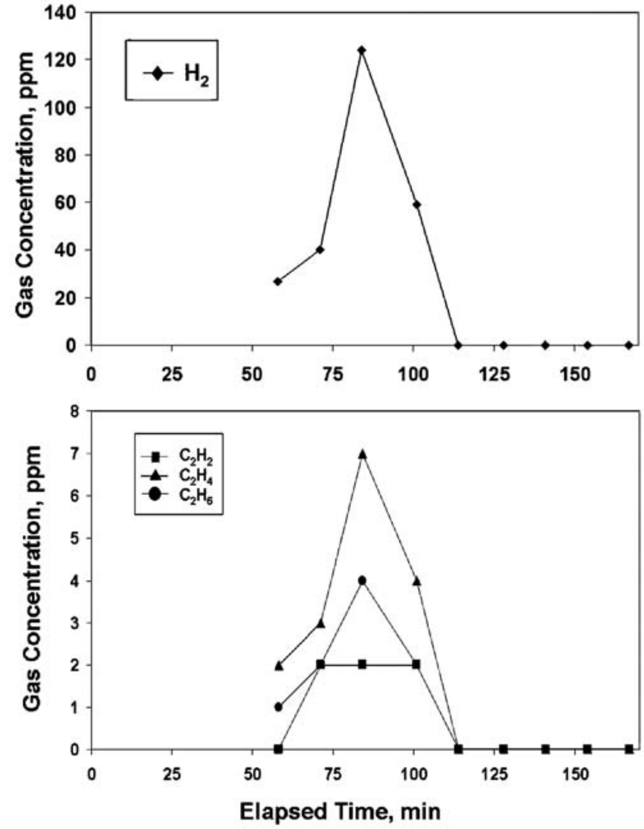

Figure 11b — Gas chromatograph data for Test 4.

after the foam application had been completed, the foam had degraded to the point were it was no longer observed on the vertical surfaces and 120 minutes after the foam application was completed the foam was no longer observed on the horizontal surfaces (on the crib blocks or the simulated mine floor). From a fire extinguishing perspective, at about 63 minutes after the foam application was completed, a small flame was observed in the lower portion of the front right crib block set and this flame continued to burn until the completion of monitoring for this test. A close inspection of this crib block set area indicated that it was sheltered from foam application and the flame was most likely a result of a glowing ember.

Figures 11a and 11b are plots of the estimated heat release rate and the products of combustion for this test. As observed in the previous tests, the fire showed an increase in heat output and CO_2 production during the intense burning event or when a crib block set fell. CO production increased at a steady rate with only slight changes when the fire intensified or when the crib block set fell. The heat output of the fire and the production of combustion gases declined dramatically when the foam extinguishing agent was applied (refer to Figs. 11a and 11b). As in the previous tests, the fire produced H_2, C_2H_2, C_2H_4 and C_2H_6 gases. The change in concentration of these gases appeared to follow the same general trend of the CO_2 gas concentration.

Crib block Test 5 (fire extinguisher agent applied). This test was designed to observe the effects of using fire extinguishers on a deep-seated crib block fire. Fire extinguishers are rated according to the extinguishing agent's effectiveness in controlling one or more classes of fire. An ABC-rated fire extinguisher is capable of addressing A, B and C class fires (combustible solid materials, flammable liquids and energized electrical equipment) and is commonly found in underground coal mines.

ABC-rated fire extinguishers contain monoammonium phosphate and/or ammonium sulfate powder that leaves a nonflammable layer of material (which melts at a low temperature) and blocks gas and heat transfer at the fuel surface. For this test, four 13.6 kg (30 lb) fire extinguishers were placed in the FSF upwind of the crib block sets. To ensure that the extinguishers were in proper working order, they were filled with ABC powder and were outfitted with new CO_2 cartridges the day before the test.

The fire test was initiated in the same manner as the previous tests. Once the gas burners were turned off, the fire for some unknown reason did not achieve a stable condition for a long period of time. At about 121 minutes into the test the rear left crib set fell, whereupon the fire intensified with some smoke rollback. At about 123 minutes into the test, the rear right crib set shifted into the front right crib set followed by an increase in fire intensity as flames were observed at the roof with smoke rollback. Approximately 3 minutes later, the fire returned to about the same level observed before the event occurred. At 128 minutes into the test, the rear right crib set fell followed by an increase in fire intensity shortly thereafter. Use of the fire extinguishers on the fire began at 161 minutes into the test when the estimated heat release rate of the fire had generally stabilized. The extinguishing work continued for about four minutes until the all of the available material was applied (Fig. 12). A total of about 45 kg (100 lbs) of ABC powder was used on the fire. The powder was observed on the horizontal surface and some of the vertical surfaces. At about 15 minutes after the application of the extinguishing agent was completed, small flames were observed in the debris from the left rear crib set and glowing embers were observed in the lower area of the front left crib set. The flames and embers continued to burn until the end of the test. Figures 13a and 13b are plots of the estimated heat release rate and the products of combustion for this test.

As shown in Fig. 13a, the increase in heat output of the fire and CO_2 production was related to the changing geometry of the wood pile as a crib block set fell. CO production increased at a steady rate with only slight changes when the fire intensified or when the crib block set fell. The heat output of the fire and the production of combustion gases declined dramatically as the extinguishing agent was applied. As in the previous tests, the fire produced H_2, C_2H_2, C_2H_4 and C_2H_6 gases (refer to Fig. 13b). The change in concentration of these gases appeared to follow the same general trend as the CO_2 and CO gas concentrations.

Figure 12 — Use of fire extinguishers during crib block fire Test 5.

Discussion

Wood cribs are used throughout underground coal mines as a secondary means of roof support. A mine fire can quickly propagate through the timbered passageways, producing life-threatening hazards such as toxic fumes, smoke and heat (Egan and Litton, 1986). During the crib fire tests, significant increases in heat output and CO_2 production were observed whenever a crib block set fell and the geometry of the burning wood pile changed or if an intense burning event occurred. CO gas production followed a gradual build-up in all of the tests and then declined as expected in the control tests as the fire reduced in size. In all of the tests, significant levels of H_2 were detected and small concentrations of C_2H_2, C_2H_4 and C_2H_6 gases were observed in the combustion product air stream. However, because of the variety of wood species used in these tests and the fact that the fire within each crib set was burning differently at the bottom of the set as compared to the top, it is impossible to determine exactly where the gases originated. As the crib block set fires evolved, the change in gas concentration of these gases appeared to follow the same general trend as either CO_2, CO or both gases together.

It was observed that the intensity of a crib block set fire could grow quickly creating localized conditions similar to that seen during a flashover event. A flashover is a term that describes an event that can occur in when a fire is burning in a closed room. Combustible gases produced by the fire and that are not wholly consumed forms a superheated gas layer at the ceiling of the room that grows laterally and downward heating nearby material to their auto-ignition temperature. Given enough oxygen, a flashover event occurs and everything in the room breaks out into open flames, instantly producing a large amount of heat, smoke and pressure. Though the conditions in the FSF during the crib block set fires test were different that those generally observed during a structural fire flashover event, the sudden uncontrolled intense burning of the crib block sets at the roof level, followed by fire growth towards the rib areas with intense smoke rollback appeared to mimic that of a very localized flashover burning event even in the presence of air flow. The crib block set fire events last for only a few minutes and the fire did not readily consume the crib blocks. This is most likely because the combustion products (due to incomplete combustion and pyrolysis of the wood material) migrate upwards through the blocks and accumulate at the roof level (in the relatively calm air spaces) along with heat from the fire. The fire then grows quickly upwards through the crib block sets and consumes the combustion products near the mine roof. Once the combustion products are consumed, the intensity of the fire is reduced to about the same level observed before the event occurred.

All of the fire-extinguishing agents tested appeared to be capable of extinguishing a deep-seated crib block fire. Each extinguishing agent performed as expected when applied to a burning surface. The fact that none of the fire-extinguishing agents completely extinguished any of the fires is attributed to the crib block set geometry and the procedure used to fight the fires, rather than limitations of the fire-extinguishing agents. The complicated geometry of the lower portion of the crib block sets was needed to create the fires; however, this geometry also created small inconspicuous areas. These areas were difficult or impossible to access with fire suppression agents given the fact that the fires could only be fought from the front and to a limited degree from the sides of the crib block sets. Furthermore, the poultry fencing used to support the crib block sets also prevented the placement of the spray nozzles inside the crib block sets thus limiting the application of the extinguishing agents.

When a crib block set fell, the geometry of the crib blocks became much more complicated and the NIOSH technicians could not directly access and separate the fallen crib blocks to apply the extinguishing agents. The need to separate the burning blocks is considered to be critically important to the process of completely extinguishing a crib block set fire. This also emphasizes the need to watch over an assumed extinguished crib block fire, as undetected and unseen hot spots could reignite the fire.

Results and conclusions

In this study, a series of large-scale, deep-seated wood crib fire tests were conducted in partnership with MSHA at the NIOSH Fire Suppression Facility to measure the various combustion products and to observe the extinguishment capability of commonly available fire suppression equipment, including dry powder fire extinguishers, water and gas-enhanced foam. These tests are part of a large-scale, deep-seated fire test program that is ongoing at the NIOSH Lake Lynn Laboratory.

During the crib block set fire tests, combustion gas information was collected in an attempt to characterize the fires.

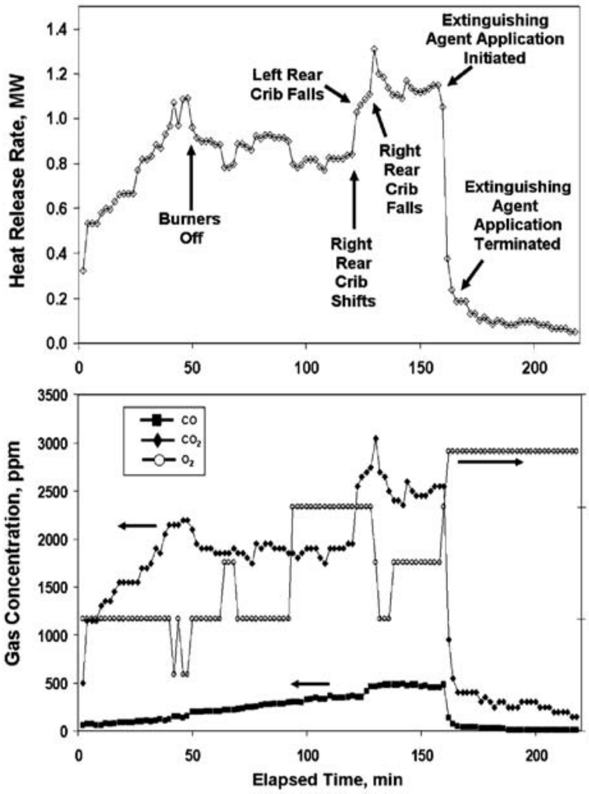

Figure 13a — Plot of estimated heat release rate and products of combustion for crib block Test 5.

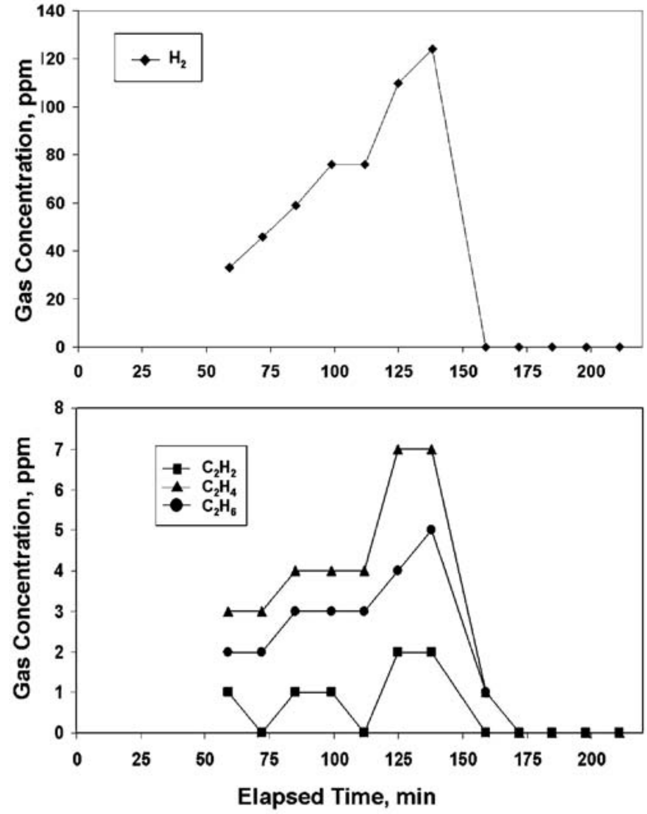

Figure 13b — Gas chromatograph data for Test 5.

In all of the tests, H_2, C_2H_2, C_2H_4 and C_2H_6 were observed in various concentrations in addition to the gases that were expected (CO_2 and CO) in the combustion gas air stream. The gases were most likely the product of incomplete combustion and pyrolysis of the wood. The presence of H_2, C_2H_2, C_2H_4 and C_2H_6 in the crib block fire combustion product air stream could offer a viable explanation as to why these gases have also been detected at some of the mine fire sites. Analysis of gas samples collected during the planned deep-seated coal fire tests will undoubtedly provide additional insight.

All of the extinguishing agents applied to the crib block fires (water, gas-enhanced foam and ABC powder) appear to be capable of extinguishing the fires if they are placed on all burning surfaces. During our tests, after the extinguishing agents were applied, the severity of the fire was significantly reduced to the point where safe evacuation from the fire area was possible and additional fire-fighting resources could have been accumulated and used to watch over the debris from the fire, separate the blocks and extinguish any and all remaining "hot spots."

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References

Egan, M.R., and Litton, C.D., 1986, "Wood crib fires in a ventilated tunnel," U.S. Bureau of Mines Report of Investigations, RI 9045, 18 pp.

Mucho, T.P., Houlison, I.R., Smith, A.C., and Trevits, M.A., 2005, "Coal mine inertisation by remote application," *Proceedings of the 2005 U.S. National Coal Show*, http://www.mining-media.com/ncs/papers/4-B%20Mucho-Smith-Trevits.pdf, 14 p., June 7-9, Pittsburgh, Pennsylvania.

NIOSH, 1999, Lake Lynn Laboratory (flyer), National Institute for Occupational Safety and Health, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, Pittsburgh, Pennsylvania, Publication No. 99-149, 1 p.

NIOSH, 2001, "A Compendium of NIOSH Mining Research 2002," National Institute for Occupational Safety and Health, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, DHHS Publication No. 2002-110, pp. 73. Washington, D.C.

Smith, A.C., Pro, R.W., and Lazzara, C.P., 1995, "Performance of Automatic Sprinkler Systems for Extinguishing Incipient and Propagating Conveyor Belt Fires Under Ventilated Conditions," US Bureau of Mines Report of Investigations 9538, 21 pp.

The Snuffer Corporation, 2006, Home page, http://www.snuffer.com, December 20.

Trevits, M.A., and Urosek, J.E., 2002, "Technology for remote mine seal construction," Preprint 02-185, presented at the SME Annual Meeting, Phoenix, Arizona, February 25-27, 4 pp.

Trevits, M.A., Smith, A.C., Gray, T.A., Crayne, L.M., and Glogowski, P., 2006a, "Remotely installed mine seals for mine fire control," Preprint 06-70, Presented at the 2006 SME Annual Meeting, St Louis, Missouri, March 26-29, 10 pp.

Trevits, M.A., Smith, A.C., Mucho, T.P., Ozment, A., Walsh, J.B., and Thibou, M.R., 2006b, "Mine fires – measuring the efficacy of gas-enhanced foam," *Proceedings of the 11th US/North American Mine Ventilation Symposium*, University Park, Pennsylvania, June 5-7, pp. 309-316.

USF Equipment and Services, 2006, Sentinel 120RS Product Flyer, 1 p.