Evaluation of deep-seated crib block fire tests

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ABSTRACT: 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, improve or modify coal mine fire-fighting strategies and methodologies through large-scale tests. Since wood is the second most abundant fuel available during a coal mine fire, it was decided that series of large-scale wood crib fire tests were 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 Introduction

In 2001, NIOSH and MSHA initiated an informal research partnership to develop new insight into the characteristics of mine fires and the limitations and capabilities of remote 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 have gained new insights into the science of mine fires and fire control and suppression technology.

In late 2006, NIOSH began 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 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 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 (Egan and Litton, 1986). 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 because this material is regularly used in underground coal mines.

2 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.

3 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 97 km (60 mi) 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 (NIOSH, 1999).

The FSF was configured to simulate a 45.7-m (150-ft) long mine entry. The interior height of the simulated mine is 2.2 m (7.2 ft) and the width is 5.5 m (18 ft). The roof of the simulated mine is made of corrugated steel bridge planks, the ribs are made of solid concrete blocks and the floor is made of reinforced concrete. The interior roof is covered with a layer of specialized fire resistant mixture of vermiculite and Portland cement and a 2.5-cm (1-in) thick layer of this material has been placed on the ribs. 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 to provide ventilation for the facility (blowing sustained airflow up to about 350 m/min (1150 ft/min) over the cross-section of the entry). The FSF is equipped with an array of chromel-alumel thermocouples (type-K) located 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 was 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.

The components of the fire gases were measured using three gas monitoring arrays. The first was a 9-point array located 6.5 m (21.2 ft) from the trailing edge of the crib block sets. The array consisted of an interconnected network of black iron pipe set across the width of the mine entry. A total of nine 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. 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 tubing line that led to a MSHA Gas Monitoring Truck. The second gas sampling array was configured in the same manner as the first and was located 29 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 4 holes drilled into 2.5-cm (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 oxygen (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 O2, CO, CO2 and methane (CH4)). Throughout each test, the data from the MSHA gas analyzers was collected at 2-minute intervals and was 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 gases analyzed included hydrogen (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 data was 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 layout of the FSF for the crib block tests is shown in figure 1. 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 0.5 m (1.5 ft) apart and were positioned near the center of the entry. As mentioned previously, the crib block sets were constructed on solid concrete blocks and located in the middle of the blocks was an impinged natural gas burner. The burners were set on the floor with the jets positioned 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 be needed for about 50 minutes to ensure that the crib fires would burn without the need to re-light 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. The ventilation air flow rates were measured at nine points in the cross-sectional area of the mine entry and an average flow rate was determined.

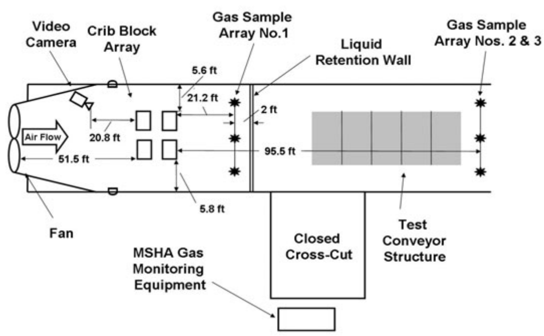

Figure 1. FSF typical set-up for a crib fire test.

4 Crib Block Composition and Crib Set Geometry

The crib blocks were comprised of a variety of mixed hardwood species including beech, cherry, maple, white and red oak and poplar. In order 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 samples of wood were sent to a testing laboratory for moisture, ultimate analysis and heating value determinations. Each crib block set was constructed on foundation consisting of 8 solid concrete blocks. A total of 34 crib blocks were stacked vertically to build each crib set (17 of the older blocks and 17 of the newer blocks). Each row of blocks was oriented perpendicular to the adjacent row. The bottom row contained four blocks (two newer blocks on the outside and two older blocks on the inside), the next row contained four blocks (two newer blocks on the inside and two older blocks on the outside). The next row contained three blocks (two older blocks on the outside and one newer block on the inside). The next row contained three blocks (two newer blocks on the outside and one older block on the inside). The remaining rows contained two blocks each alternating between the new and older blocks in a row. The blocks were secured to the roof with wedges as needed. In order 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.

5 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. The estimated heat release rate of the fire or estimated energy output 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 was determined using the amount of CO and CO_2 in the combustion product air stream and the rate of consumed oxygen. The methodology used for making the estimated heat release rate calculations is defined in detail in by 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.

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 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. A brief summary of each test follows.

5.1 Test Nos. 1 and 2 (Control Tests)

During test No. 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 back side (downwind side) of each crib block set (figure 2). 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.

Figure 2. Control test - Burning crib block sets

As discussed earlier, test No. 2 was designed to serve as the alternate control base case for the tests and involved four crib block sets that were enclosed in a steel framework. A plot of the estimated heat release rate and the products of combustion for both control tests are shown in figure Nos. 3A-C. From the figures, it appears that test No. 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 No. 2. Also, the gas chromatograph data (figure 3C) shows that H_2, C_2H_2, C_2H_4 and C_2H_6 gases was 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 No. 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 No. 2.

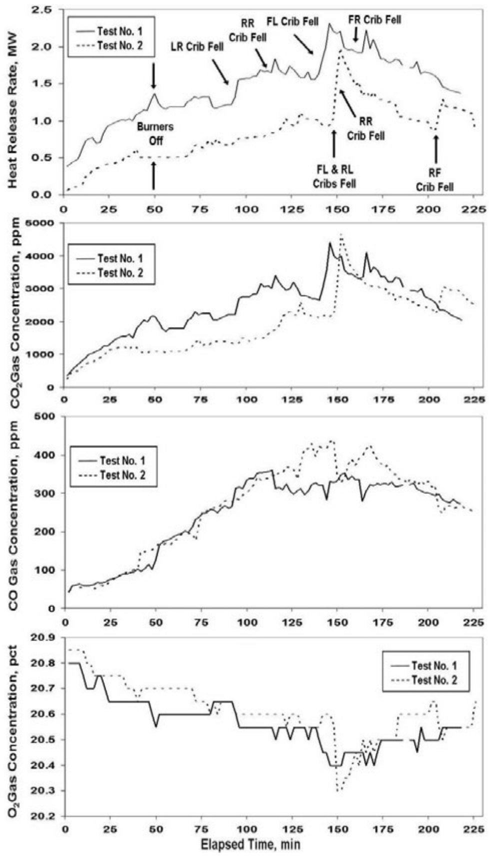

Figure 3A. Plot of estimated heat release rate and products of combustion for crib block tests Nos. 1 and 2.

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

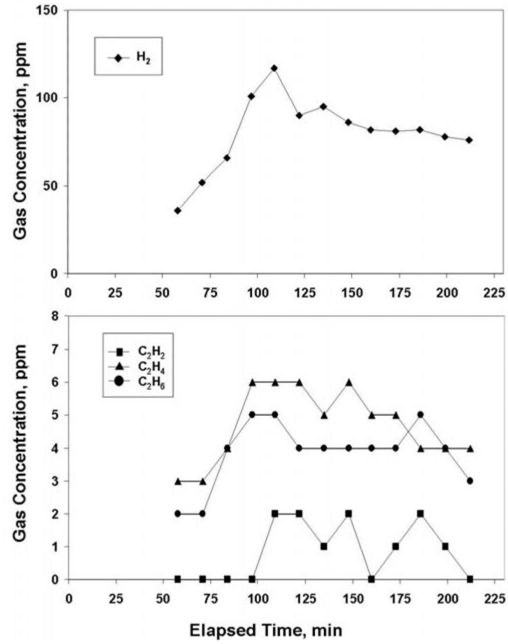

Figure 3B. Gas chromatograph data for test No. 1.

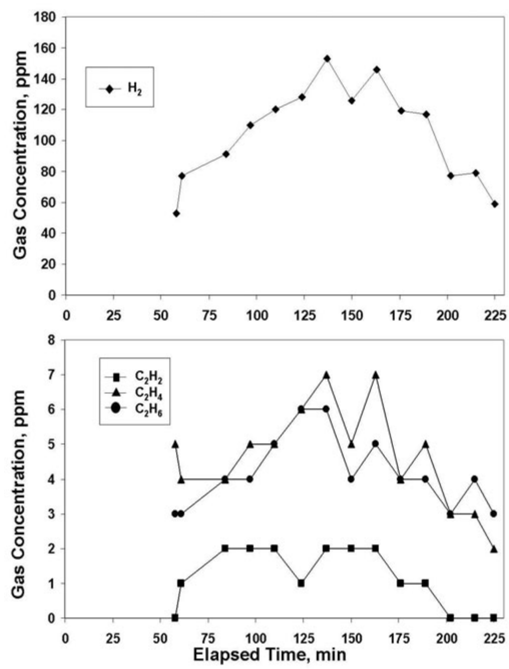

Figure 3C. Gas chromatograph data for test No. 2.

proximity of the fallen burning crib blocks and the associated heat build-up. As planned during test No. 2, the steel framework did indeed hold the crib sets upright longer than the unconfined crib block sets in test No. 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.

5.2 Test No. 3 (water suppression agent)

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 9,100 liters (2,400 gallons) of water was available from the truck for the test. Water was supplied through the fire hose to the nozzle at a rate of 284 l/min (75 gal/min) at 690 Kpascal (100 psi). The test was initiated in the same manner as the control tests. 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.

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 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 4 minutes when the technicians decided the fire had been extinguished and a total of 300 gallons of water was used (figure 4). 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 4 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.


Figure 4. Use of fire hose during crib block fire test No. 3.

5.3 Test No. 4 (gas-enhanced foam suppression agent)

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. 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, 2006). The system used was capable of producing 9,100 liters (2,400 gallons) of gas enhanced foam using a mixture of water, a small amount of Mine Fire Fighting Foam® (MFFF) concentrate and nitrogen gas. The system can discharge up to 1135 l/min (300 g/min) 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. Gas-enhanced foam application began 103 minutes into the test when the estimated heat release rate of the fire had generally stabilized (figure 5). About 1 minute later, the right rear crib block set fell down. Foam application continued for about 8 minutes when the technicians decided that the fire had been extinguished. A total of 9,100 liters (2,400 gallons) of gas-enhanced foam (the entire capacity of the system) was used. At about 40 minutes 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 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.

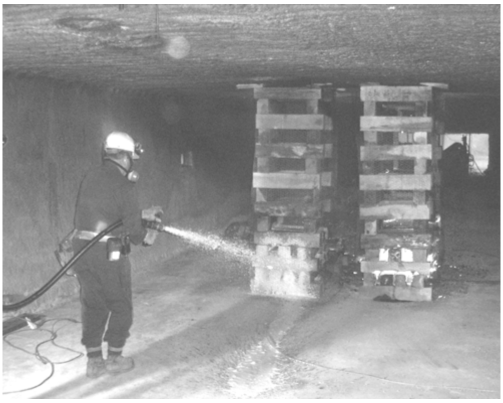

Figure 5. Use of gas-enhanced foam during crib block fire test No. 4.

Figure 6. Use of fire extinguishers during crib block fire test No. 5.

5.4 Test No. 5 (fire extinguisher agent)

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 sulphate powder that leaves a non-flammable 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. 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 (figure 6). The extinguishing work continued for about four minutes until the all of the available material was applied. A total of about 45.4 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.

6 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 and were most likely the product of incomplete combustion and pyrolysis of the wood. 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 intense burning event. During these events, there was a 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. The intense burning 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) migrated upward through the blocks and accumulated at the roof level (in the relatively calm air spaces) along with heat from the fire. The fire then grew quickly upwards through the crib block sets and consumed the combustion products near the mine roof. Once the combustion products were consumed, the intensity of the fire was 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 open 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.

7 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. 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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