UNDERSTANDING MINE FIRES BY DETERMINING THE CHARACTERISTICS OF DEEP-SEATED FIRES

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Abstract

A mine fire represents one of the most dangerous and challenging safety issues facing underground mine operators. Given the right circumstances, a mine fire can occur at any location in the active or abandoned mine workings, can quickly grow beyond control, and threaten the welfare and livelihood of the entire underground workforce. The National Institute for Occupational Safety and Health (NIOSH), in partnership with the Mine Safety and Health Administration (MSHA), has been conducting an in-depth program of research addressing mine fire prevention, early and reliable fire detection, and mine fire suppression technologies. One portion of this program is focused on understanding the characteristics of mine fire combustion products and flame spread through large scale deep-seated (firmly established) fire tests and use of computational fluid dynamics (CFD) modeling. In this study, two deep-seated fire tests were conducted; one fire consisted of coal material and the other utilized the two most abundant fuel sources found in a coal mine: coal and wooden cribbing blocks. The fires were burned to completion while the combustion products were collected and analyzed. In addition, an array of thermocouples was placed within the body of the material to measure flame spread rate. The coal fire test information was then used to develop a CFD model of the fire. This paper describes the fire tests, provides insight into characteristics of flame spread, and presents the CFD modeling work results.

Introduction

Fire spread in a coal mine will depend upon the thermal and physical properties of the most abundant fuel sources (including coal, wooden mine roof supports, and conveyor belts), the mine's ventilation system, and the size of the mine opening [1]. Because fuel sources are typically distributed throughout a mine, a fire can spread quickly over large lateral distances. Moreover, mine fires can be especially perilous because the toxic fire products can quickly spread far beyond the fire zone and thereby expose all underground miners to dangerous and deadly conditions.

The leading causes of U.S. mine fires include flame cutting and welding operations, frictional heating and ignitions, electrical shorts, mobile equipment malfunctions, and spontaneous combustion [2]. The fact that mine fires continue to occur emphasizes the importance of recognizing and eliminating potential fire hazards and the overall need for improved fire control and suppression technology. The NIOSH mine fire research program is addressing a broad spectrum of problem areas facing the U.S. mining industry. The intent of the work is to provide the mining industry with an understanding of the conditions that could lead to a fire, the capability to detect unusual heating or fire conditions, and the technology to suppress and extinguish a fire. Work under this research program includes testing, evaluating, improving and modifying coal mine fire-fighting strategies and methodologies through large-scale tests. One portion of this work is focused on understanding the characteristics of mine fire combustion products and flame spread through deep-seated fire experiments and use of CFD modeling.

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, NIOSH researchers and MSHA technical specialists 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. This study represents the second stage of a series of deep-seated fire tests. The first study examined the combustion characteristics of wood crib blocks and direct application of fire suppression agents [3]. Future work will concentrate on large-scale deep-seated coal fires in an underground setting followed by remote application of fire suppression agents. It is anticipated that these experiments combined with follow-up CFD modeling work will provide significant information about combustion products and flame spread rates and will assist in furthering our understanding of the evolution and growth of a mine fire.

Objective and Approach

The objective of this study was to conduct two deep-seated fire experiments, including a coal fire and a mixed fuel fire (coal and wood cribbing blocks combined), to collect combustion product information, measure flame spread rates and to study the mechanics of the fire through computer modeling.

NIOSH Fire Suppression Facility

The fire tests were conducted at the NIOSH 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 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 work is conducted [4].

The FSF was configured to simulate a 150-ft long mine entry. The interior height of the simulated entry is 7.2 ft and the width is 18 ft. The roof of the simulated entry is made of corrugated steel bridge planks, the ribs are made of 8-in thick mortared solid concrete blocks and the floor is made of reinforced concrete. The interior roof is covered with a 2-in thick layer of Fendolite M-II ® (a specialized fire resistant mixture of vermiculite and Portland cement) and a 1-in thick layer of Fendolite M-II® has been placed on the ribs.[1] For ventilation, a 6-ft diameter variable speed axivane fan (equipped with a pneumatic controller to adjust fan blade pitch) was installed at one end of the simulated entry. The fan can provide blowing sustained airflow up to about 1150 fpm over the cross-section of the entry. Two doors, which permit access to the inside of the FSF, are located about 47 ft from the fan. Figure 1 shows the exterior of the FSF.

Figure 1. Fire Suppression Facility.

The FSF is equipped with an array of chromel-alumel thermocouples (type-K) projecting 1.2-in down from the mine roof. The thermocouples are spaced at 10-ft intervals starting about 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 fire tests, temperature data was collected at 10-second intervals. Radiation corrections were not made in the temperature data.

The components of the fire gases were measured using a 9-point gas sampling array located 20 ft from the trailing edge of the burn box used to contain the fires. The array consisted of an interconnected network of ½-in diameter black iron pipe set across the width of the mine entry. A total of nine, 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. 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

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

was connected to a tubing line that led to the NIOSH and MSHA gas analysis equipment.

The NIOSH infrared gas analyzers measured oxygen (O_2), carbon monoxide (CO) and carbon dioxide (CO_2) gas concentrations and the resultant data were collected at 10-second intervals and recorded by a computer-based data acquisition system. In addition, gas samples were collected periodically over 3- to 4-minute intervals from the gas sampling array and were analyzed using gas chromatography. Chromatography analysis of each of the gas samples took about ten minutes to complete, therefore during each test a sample was collected and analyzed approximately every 13-15 minutes. The gases analyzed included hydrogen (H_2), O_2, CO, CO_2, methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), and ethane (C_2H_6). The NIOSH and MSHA gas analyzers and the MSHA gas chromatograph were calibrated before each test. After each test, the MSHA gas analyzers were checked with fresh air to determine instrument drift.

Composition of the Coal and Wood

The coal used in each test was mined from the Pittsburgh Coalbed. The coal was cleaned and sorted (mostly 2-in sized pieces) and was stored outside for about 6 months. Two coal samples were collected for laboratory analyses, including ultimate, proximate and heating value determination. The wooden cribbing blocks were comprised of a variety of mixed hardwood species including ash, cherry, maple, white and red oak, and poplar. The blocks were 14 to 20 months old and had been stored underground at the LLL for about a year prior to the tests. Ten crib blocks (each block measured 6 in high, by 8 in wide by 16 in long) were randomly collected and 3-in cube-shaped samples were cut from each of the selected crib blocks and were sent to an independent testing laboratory for moisture, ultimate analysis, and heating value determinations. The averaged laboratory data for the coal and wood crib samples are shown in Table 1.

Deep Seated Fire Tests

A 3-ft-long by 2-ft-wide by 1-ft-deep box was constructed to hold the coal and wood during the fire tests. Legs (6 in) were attached to elevate the box and prevent heat damage to the FSF floor. The sides, back, and bottom of the box were constructed of expanded metal and 1 in angle iron was used as the frame (the front and top of the box was left open). The box was equipped with 16 chromel-alumel thermocouples (type-K) projecting 8 in inward from the sides. The thermocouples were spaced at 4-in and then 8-in intervals starting from the front of the box and leading towards the back of the box. The alignment of the thermocouples formed two layers of 8 units and simultaneously formed four rows of 4 units. This arrangement permitted researchers to construct 3-dimensional views of the fires. The thermocouples were connected via a wire network to the computer-based data acquisition system mentioned previously.

Table 1. Averaged laboratory data from coal and crib block samples.

Parameter	**Coal**			**Wood**		
Sample Condition	AR[1]	Dry	DAF[2]	AR	Dry	DAF
Moisture, pct	8.90	-	-	14.95	-	-
Proximate Analysis						
Ash	7.23	7.94	-	0.68	0.79	-
Volatile Matter	33.73	37.02	40.21	72.54	85.27	85.95
Fixed Carbon	50.15	55.05	59.80	11.85	13.94	14.05
Ultimate Analysis						
Hydrogen	5.67	5.14	5.58	6.39	5.54	5.59
Carbon	68.63	75.34	81.83	42.21	49.63	50.03
Nitrogen	1.26	1.38	1.50	0.16	0.19	0.19
Sulfur	0.66	0.72	0.79	0.12	0.14	0.14
Oxygen	16.56	9.50	10.32	50.44	43.71	44.06
Ash	7.23	7.94	-	0.68	0.79	-
Heating Value, Btu/lb	12,202	13,394	14,549	7,184	8,446	8,513

1 As Received.

2 Dry Ash-Free.

The fires were initiated using a natural gas burner that was equipped with 60 stainless steel jets (with a rated heat output of 44 to 114 kW). The burner was tilted on an angle upward toward the box to evenly spread flame across the opened front of the box. 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 combustion products. It was arbitrarily decided to operate the burners for 45 to 60 minutes to ensure that the fires would burn without the need to re-light the burners. A steel plate was placed over the burners on an angle away from the fan across the front of the box creating an air deflector. This deflector was necessary to keep the fires burning. Figure 2 shows the position of the box in the FSF.

Prior to igniting the fires, the ventilation flow rate was measured in front of the burn box and at the gas sampling array. At each location, the ventilation air flow rate was measured at nine points in the cross-sectional area of the mine entry and an average flow rate was determined. Table 2 shows the averaged ventilation air flow rate data for the tests. It should be noted that the ventilation flow rate for Test 2 was more than double that of Test 1 because fan problems precluded a sustainable lower flow rate.

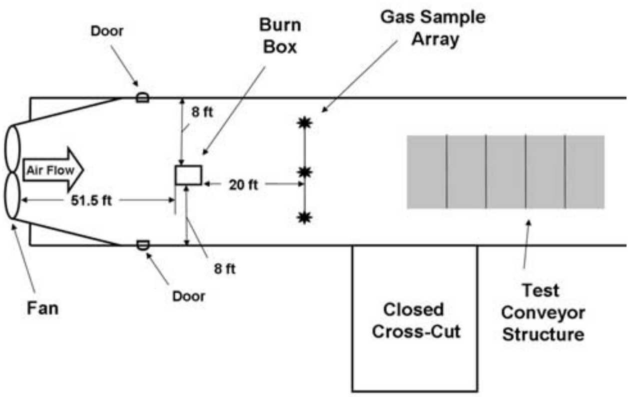

Figure 2. Layout sketch of the FSF for the deep seated fire tests.

Table 2 – Average ventilation flow rate information for the fire tests.

Test No.	1	2
Ventilation flow rate in front of burn box, ft/min.	160	350
Ventilation flow rate at the gas sampling array, ft/min.	150	300

Deep Seated Fire Test 1

As mentioned previously, two deep-seated fire tests were conducted in this study. The first involved 202.5 lbs of coal. The coal was placed into the burn box so that the leading edge of the pile facing the fan measured 4 in deep. The pile was tapered upward towards the back of the box and reached its maximum depth of 8 in at the midpoint of the box. Two layers of 8 thermocouples were placed in the pile. The top layer was positioned below the surface of the coal and the bottom layer was positioned above the expanded metal surface. Figure 3 shows two views of the box and location of the thermocouples. Figure 4 shows a picture of the box just prior to igniting the burner.

After the burner was turned off (after 45 minutes of elapsed time), it was observed that the leading edge of the fire was burning intensely. This burning condition was needed to ensure that the fire would burn to completion. During the test, the collected gas samples showed only CO and CO_2 were detected in the air stream and the concentration of these gases was below the lower reliable limit of detection. This was most likely due to the fact that the fire was small relative to the size of the FSF and the ventilation flow rate. Therefore, this data could not be used to calculate the heat release rate of the fire. The fire burned slowly from the front to back in 70.5 hrs and reached a maximum temperature of 788°C. Figure 5 shows the time-temperature traces from the thermocouples for the test. The figure presents four vertical slices through the coal pile at 4-, 12-, 20-, and 28-in (measured from the leading edge of the box) and shows the progression of the fire at these positions over time.

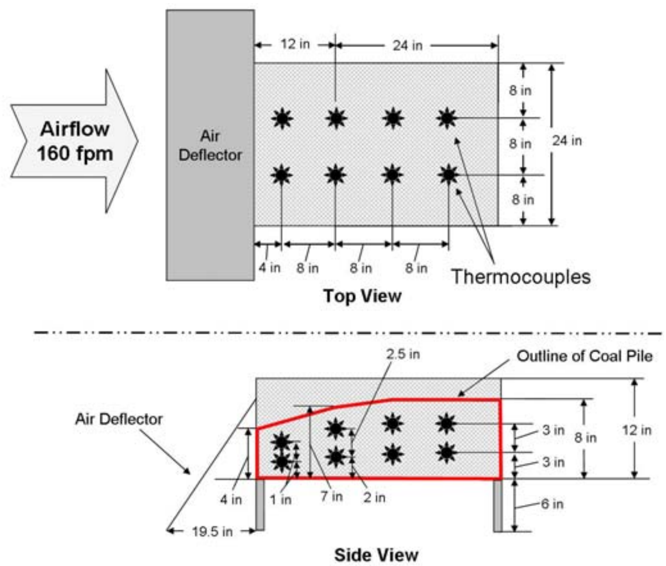

Figure 3. Airflow, layout of the coal and thermocouple array for Test 1.

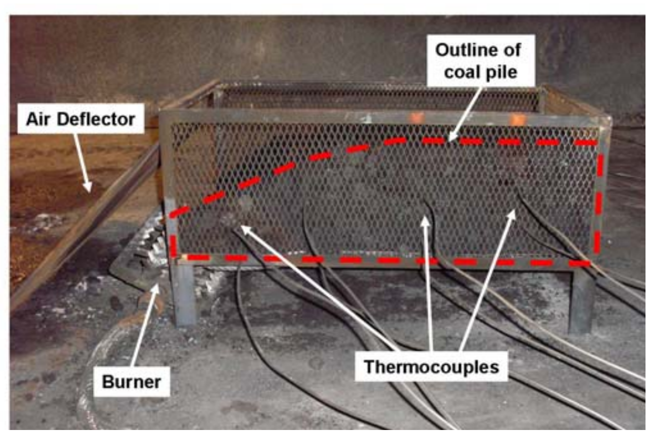

Figure 4. Side view of box just prior to Test 1.

The varied shape of the temperature plots from Test 1 are believed to be caused, in some cases, by burning coal falling away from a thermocouple resulting in a temperature decline and in other cases from burning coal falling onto a thermocouple causing the temperature to increase or be sustained for a longer period of time.

A pyrolysis temperature of 525°C was used in this study and when the temperature at a thermocouple reached this value, the flame front was considered to have reached that location [5]. The average flame spread rate of this fire was calculated to be 1.1 in/hr. This is a slower rate than those measured by Smith (1.9 and 2.1 in/hr) for a set of similarly sized coal fires [6]. Also in the previous work conducted by Smith, the ventilation flow rate was 380 $\pm$ 20 ft/min as compared to 160 ft/min used in this test which could account for some portion of the difference in the flame spread rates [6].

As mentioned earlier, 202.5 lb of coal was consumed in 70.5 hrs yielding a mass-loss rate of 2.9 lb/hr. Using the heating value of 13,394 Btu/lb from Table 1, the mass-loss rate converts to a heat release rate of 650 Btu/min (11.4 kW). The amount ash remaining after Test 1 was 8.8% which was only slightly higher than the 7.2% average value shown in Table 1, indicating that most if not all of the coal was consumed in the fire.

Deep Seated Fire Test 2

As described previously, the material used for this fire was a blend of the two most common fuel sources found in a coal mine, namely coal and wooden cribbing blocks. The wood crib blocks were cut into two sizes to fit the scale of the box. The larger cut size blocks measured 2.8 in by 2.5 in by 22 in and the smaller cut blocks measured 2.8 in by 2.5 in by 7.9 in. A total of 7 large and 9 small blocks were used in this test and the blocks consisted of a mix of the various hardwoods described previously. A row of blocks (3 large and 3 small) was placed into the burn box with the long axis of the blocks parallel to the long axis of the box. Coal was placed into the box to fill the spaces between the blocks. A second row of 4 large blocks was placed perpendicular to the first row. Again, coal was used to fill in the open space between the blocks. The top row of blocks was formed by placing 6 small blocks perpendicular to the previous row and coal was used to fill in the open spaces. A total of 170 lbs of coal and 42.8 lbs of wood were used in this test.

The wood and coal mixture was placed in the burn box so that the leading edge facing the fan measured 6 in deep. The mixture was tapered upward towards the back of the box and at the midpoint reached a maximum depth of 8 in. As in Test 1, two layers of 8 thermocouples were used. The top layer of thermocouples was positioned above the second row of wood and the bottom layer was positioned above the lowest level of wood. Figure 6 shows two views of the box and location of the thermocouples for the test. Figure 7 shows a picture of the box just prior to igniting the burner.

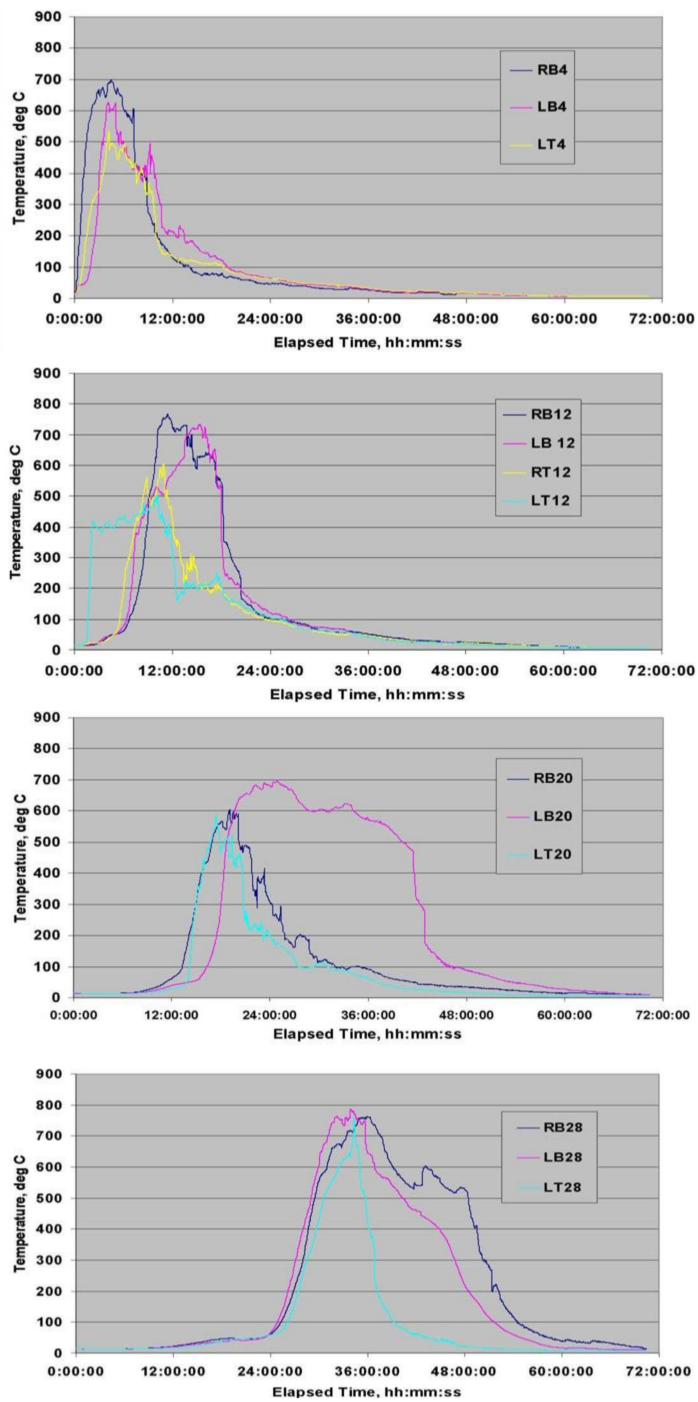

Figure 5. Time-temperature traces from thermocouples for Test 1. The terms RB, LB, RT and LT refers to the right bottom, left bottom, right top and left top respectively. Note data from RT4, RT20 and RT28 was omitted due because of instrument failure.

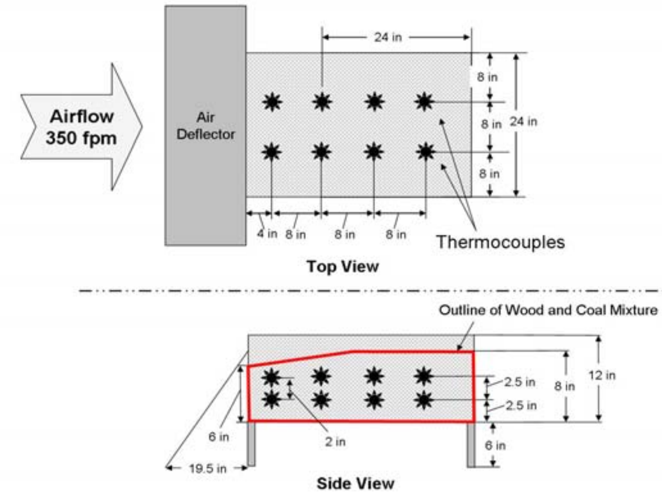

Figure 6. Airflow, layout of the coal and thermocouple array for Test 2.

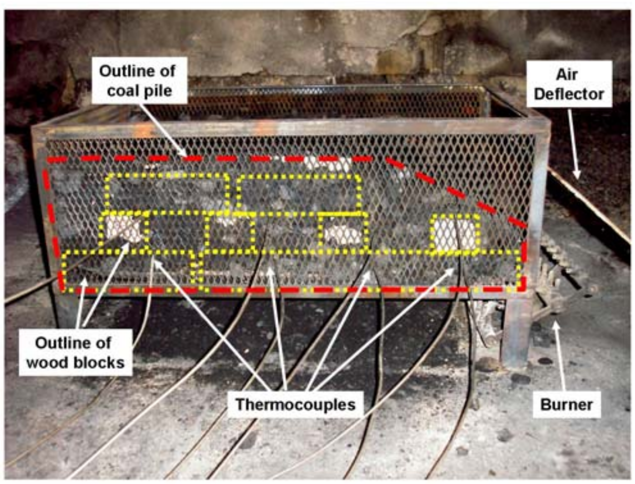

Figure 7. Side view of box as configured for Test 2.

The ventilation air was increased by almost 100% for this test because there were problems maintaining a sustained airflow at lower flow rates. The burner was turned off after 60 minutes and the fire was observed to be burning intensely. As in the previous test, the collected gas samples showed that the concentration of the combustion products in the air stream were below the lower reliable limit of detection. This was again most likely due to the fact that the fire was small relative to the size of the FSF and the ventilation flow rate. Therefore, this data could not be used to calculate the heat release rate of the fire. Figure 8 shows (as in the previous test) time-temperature traces from the thermocouples and presents four vertical slices through the coal and wood mixture at 4-, 12-, 20-, and 28-in from the leading edge of the box. The figure illustrates the progression of the fire at these positions over time.

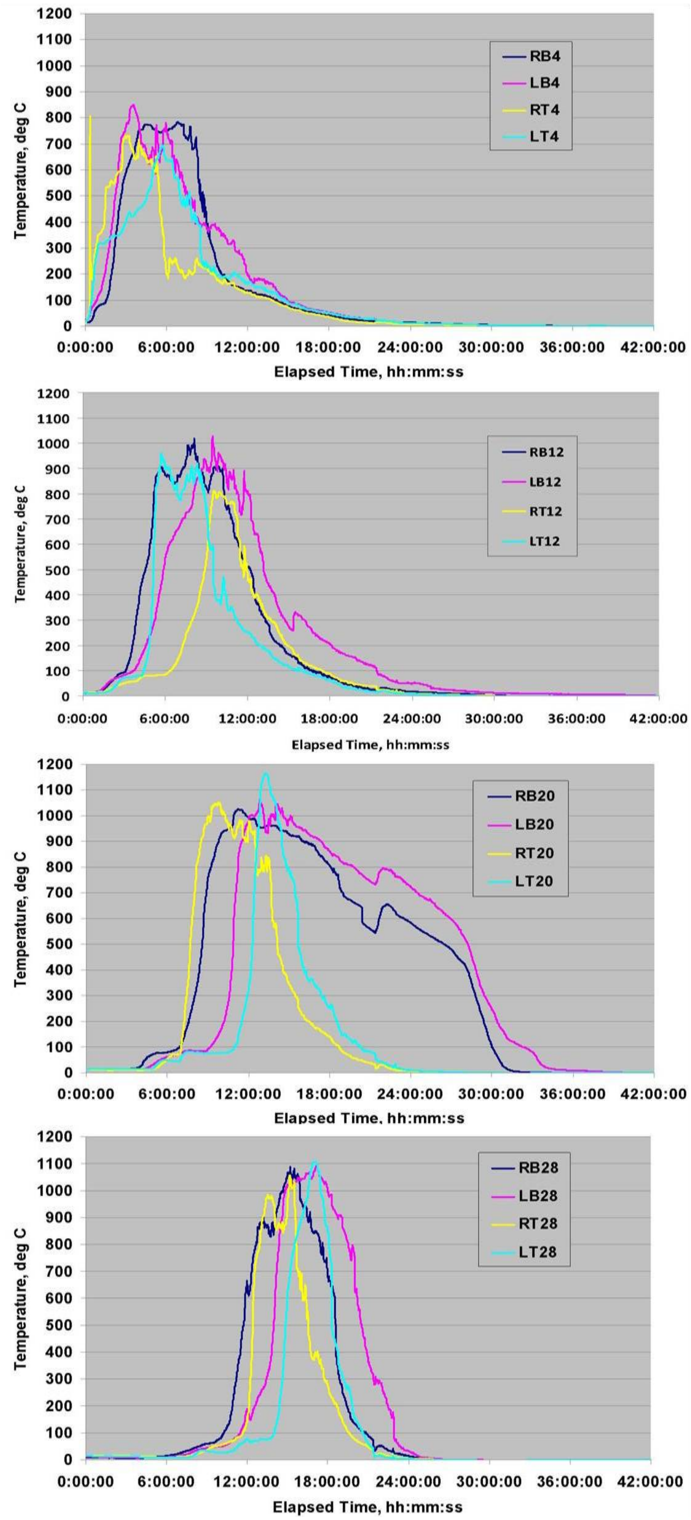

Figure 8. Time-temperature traces from the thermocouples for Test 2.

As in Test 1, the varied shape of the temperature plots from Test 2 are believed to be caused, in some cases, by burning material falling away from a thermocouple resulting in a temperature decline and in other cases from burning material falling onto a thermocouple causing the temperature to increase or be sustained for a longer period of time.

The mixed fuel fire burned faster than the coal fire and was completed in about 36 hrs. The maximum observed temperature of this fire was 1163°C. As in Test 1, the flame spread rate of the fire was measured when the temperature of the fire was reached 525°C at a thermocouple location. The average flame spread rate was calculated to be 2.0 in/hr (about 82% faster than the coal fire in Test 1). Again, this faster rate can be attributed to the increased ventilation flow rate and the fact that the wood most likely burned at a faster rate than the coal.

As mentioned previously, 170 lb of coal was consumed in 36 hrs yielding a mass-loss rate of 4.7 lb/hr. Using the heating value of 13,394 Btu/lb from Table 1, the mass-loss converts to a heat release rate of 1050 Btu/min (18.4 kW). This fire also consumed 42.8 lbs of wood yielding a mass-loss rate of 1.2 lb/hr. Using the heating value of 8,446 Btu/lb from Table 1, the mass-loss converts to a heat release rate of 170 Btu/min (3.0 kW) producing a combined heat release rate for the fire of 1220 Btu/min (21.4 kW). The amount ash remaining after Test 2 was 7.2% which was only slightly higher than the 5.9% value calculated from the coal and wood ash data shown in Table 1, indicating that most if not all of the coal and wood was consumed in the fire.

CFD Modeling of Flame Spread for the Coal Fire

Flame spread in the coal fire was simulated using Fire Dynamics Simulator (FDS), a computational fluid dynamics (CFD) program developed by National Institute of Standards and Technology. Because of its very complicated geometry, no attempt was made to simulate the mixed fuel fire. FDS is a three-dimensional, large eddy simulation model developed to study the transport of smoke and hot gases during a fire in an enclosed space. FDS is the most widely used large eddy simulation model in the fire science field and has demonstrated good agreement with experimental data in numerous validation studies. The model uses finite difference techniques to solve the Navier-Stokes equations numerically for fluid flow with a mixture fraction combustion model. Most mine combustibles undergo combustion by a gas phase reaction of the volatiles generated by the pyrolysis of the material. The pyrolysis front advances as a reaction front into the solid fuel leaving behind a char layer [1]. The FDS includes a pyrolysis model.

Figure 9 shows the physical model of the coal pile, the burner, and the FSF. The dimensions for the model FSF were 18 ft wide by 7.2 ft high (the same as the actual FSF). For the simulation the length of the FSF was limited to 19.7 ft. The coal was modeled as a rectangular volume with dimensions of 3 ft long by 2 ft wide by 8 in high. The burner was modeled using its average heat release rate of 81 kW. In the simulation, the burner was kept on for 50 minutes. The airflow velocity at the inlet of the model FSF was 157 fpm similar to Test 1. Eight surface thermocouples were created in the simulation and were designated as T1 to T8. The thermocouples were located in the top of the pile similar to those in Test 1. Thermocouples T1 and T5 were located at the 4 in position, T2 and T6 were at 12 in position, T3 and T7 were at the 20 in position and T4 and T8 were at the 28 in position (as measured from the leading edge of the box).

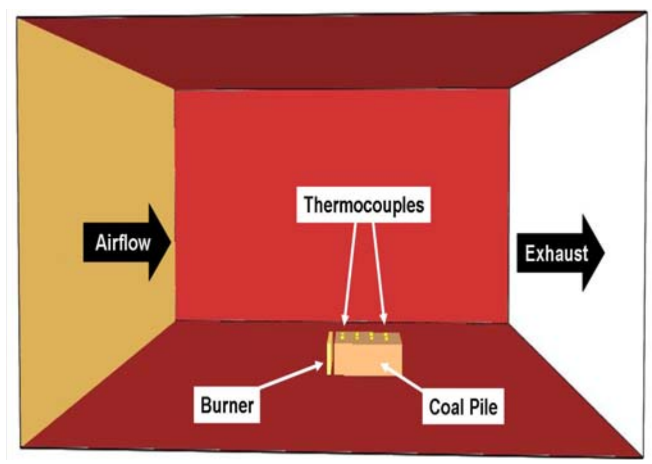

Figure 9. The physical model of coal pile, burner and the simulated FSF.

In the simulation, the coal was treated as a continuous-medium with constant physical properties. The coal density was 1330 kg/m^3; coal specific heat was 1.05 kJ/kg-K; coal conductivity was 0.24 W/m-K; and the heat of combustion for the coal was 13,460 Btu/lb. In the simulation, the pyrolysis front advances with an endothermic heat of reaction. The heat of pyrolysis was 209 kJ/kg, and the pyrolysis temperature of the coal was 525°C [5].

Figure 10 shows temperatures at different thermocouple locations as calculated in the simulation. Only temperatures at thermocouples T1-4 are presented. As mentioned previously, the varied shape of the temperature plots from Test 1 are believed to be caused, in some cases, by burning coal falling away from a thermocouple resulting in a temperature decline and in other cases from burning coal falling onto a thermocouple causing the temperature to increase or be sustained for a longer period of time. In the simulation however, this could not be duplicated because the coal was treated as a continuous medium and as such the temperature plots do not fall off quickly as observed in Test 1. It can be seen from the figure, the surface temperature increased slowly at the beginning except for thermocouple T1 which increased quickly because it was close to the ignition burner. This stage is a typical pre-heating period. After reaching about 450°C, the temperature increased very quickly to 700°C, indicating the arrival of the flame. The flame spread rate was 2.1 in/hr from T1 to T2, 2.9 in/hr from T2 to T3 and 3.1 in/hr from T3 to T4.

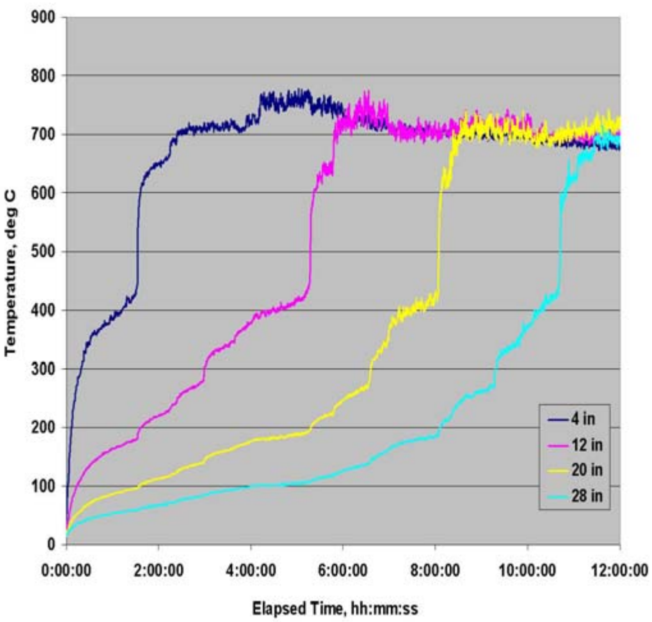

Figure 10. Time-temperature traces from the thermocouples for the CFD coal fire simulation.

Discussion

Figure 11 shows time-average temperature traces for thermocouples at each location for both tests. The plots were constructed by determining the average temperature for all thermocouples at each position (4-, 12-, 20-, and 28-in from the leading edge of the box) over the life of the test. The plot shows how differently these fires behaved. The coal fire burned slower and at a lower average temperature while, the mixed fuel fire burned faster and was significantly hotter than the coal fire. Part of the difference between the two tests can be attributed to the fact that the wood components in Test 2 were not evenly sized relative to the coal pieces. This difference was considered in the design of the experiment and it was decided that the larger wood pieces more closely approximated that found in a coal mine. Given that the wood burned at a faster rate than the coal, the flame front would also move faster through the coal and wood mixture. Also, some of the difference between the two fires can be attributed to the variation in ventilation air speed. A CFD analysis by Edwards and Hwang showed that the flame spread rate in a simulated coal lined tunnel was strongly sensitive to ventilation air speed [1]. Further experimentation is warranted to indentify the exact relationship between flame spread and ventilation air speed.

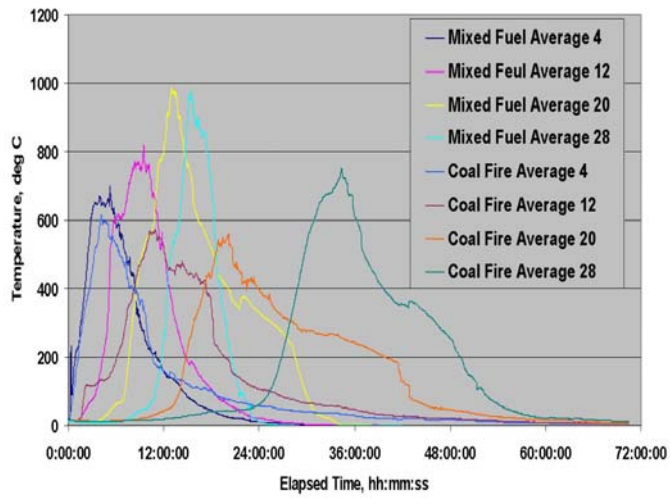

Figure 11. Time-average temperature plots at each position for Tests 1 and 2.

Table 3 shows a comparison of the parameters from Test 1 with the FDS simulation of the coal fire. Compared to Test 1, the maximum surface temperatures as estimated in the simulation are very close to those measured in the test. However the simulation overestimated the flame spread rates. This is probably because the coal pile was treated as a continuous medium in the simulation, while in Test 1 it consisted of packed pieces of coal. With the continuous medium, heat conduction is stronger than in packed coal pieces leading to higher flame spread rate.

Table 3 Comparison of Test 1 data to FDS simulation.

Parameter	Test 1	FDS Simulation
Ventilation rate, fpm	160	157
Average flame spread rate, in/hr	1.1	2.7
Maximum temperature, °C	788	777

Summary

In this study, two, deep-seated fire tests including a coal fire and a mixed fuel fire (coal and wood combined), were conducted in partnership with MSHA at the NIOSH Fire Suppression Facility to collect combustion product information, measure flame spread rates, and to study the mechanics of the fire through computer modeling. These tests are part of a large-scale fire test program that is ongoing at the NIOSH Lake Lynn Laboratory. Unfortunately because of the small size of the fire tests, relative to the FSF, we were unable to collect meaningful fire combustion product information.

A comparison of the two fire tests showed that the fires behaved differently with the coal fire burning more slowly and achieved a lower temperature than the mixed fuel fire. Part of the difference can be attributed to the fact that the wood components in Test 2 were not evenly sized relative to the coal pieces. This difference was considered in the design of the experiment and it was decided that the larger wood pieces more closely approximated that found in a coal mine. Given that the wood burned at a faster rate than the coal, the flame front would also move faster through the coal and wood mixture. Additionally, the difference in the ventilation flow rates between the two tests undoubtedly contributed to the rate of flame spread (1.1 in/hr with a ventilation flow rate of 160 ft/min for the coal fire test versus 2.0 in/hr with a ventilation flow rate of 350 ft/min for the mixed fuel fire test).

CFD modeling of the Test 1 showed the maximum surface temperatures in the simulation were very close to those measured in the test. But the flame spread rates from the simulation are higher than those estimated in the test. This is probably because that the coal pile was treated as a continuous medium in the simulation, while in Test 1 it consisted of packed pieces of coal. The results from this modeling exercise will be used in the design of the follow-up large-scale underground deep seated coal fire experiments with remote fire suppression applications.

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