Post-explosion observations of experimental mine and laboratory coal dust explosions

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Abstract

The Pittsburgh Research Laboratory (PRL) of the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) conducted joint research on dust explosions by studying post-explosion dust samples. The samples were collected after full-scale explosions at the PRL Lake Lynn Experimental Mine (LLEM), and after laboratory explosions in the PRL 20-L chamber and the Fike 1 m^3 chamber. The dusts studied included both high- and low-volatile bituminous coals. Low temperature ashing for 24 h at 515 °C was used to measure the incombustible content of the dust before and after the explosions. The data showed that the post-explosion incombustible content was always as high as, or higher than the initial incombustible content. The MSHA alcohol coking test was used to determine the amount of coked dust in the post-explosion samples. The results showed that almost all coal dust that was suspended within the explosion flame produced significant amounts of coke. Measurements of floor dust concentrations after LLEM explosions were compared with the initial dust loadings to determine the transport distance of dust during an explosion. All these data will be useful in future forensic investigations of accidental dust explosions in coal mines, or elsewhere.

Keywords: Dust; Explosion; Mine explosion

1. Introduction

Much progress has been made in preventing underground coal mine disasters, but explosions still occur, sometimes producing multiple fatalities. In an explosion, all underground miners are at risk. There were serious underground coal mine explosions in July 2000 in Utah (2 fatalities and 8 injuries), in September 2001 in Alabama (13 fatalities and 3 injuries), in January 2006 in West Virginia (12 fatalities and 1 injury), and in May 2006 in Kentucky (5 fatalities). There have been other mine explosions in the USA in recent years that did not result in any injuries, but the mine recovery efforts took several months. These events show that the mine-explosion problem has not yet been solved. Therefore, the Pittsburgh Research Laboratory (PRL) of the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) have conducted joint research to improve the forensic investigation techniques for accidental coal mine explosions.

Explosions in underground coal mines and surface facilities such as processing plants are caused by accumulations of flammable gas and/or combustible dust dispersed in air in the presence of an ignition source. Research on the causes and mechanisms of gas and dust explosions is needed as a basis for the development of techniques and strategies for explosion prevention, suppression, and mitigation. In the coal mining industry, rock dust (usually limestone) is added to the coal dust deposits to act as a heat sink and inhibit flame propagation. If a sufficient amount of rock dust is added to the coal dust, the mixture is rendered inert. The rock dusting regulations are based on the results of full-scale experimental mine tests as summarized by Nagy (1981). The rock dusting requirements are specified in Title 30, Section 75.403 of the US Code of Federal Regulations (2006).

NIOSH-PRL conducts dust explosion research in its Lake Lynn Experimental Mine (LLEM) and in laboratory vessels. Post-explosion dust sampling is part of this research effort. Analysis of these samples provides MSHA with valuable information concerning the characteristics of dust samples collected after well-documented explosions. This information can then be used by MSHA in future explosion accident investigations. Accurate forensic investigations are important for thorough accident interpretation and follow-up recommendations to prevent future occurrences. Some preliminary data from post-explosion dust samples were presented previously (Cashdollar & Going, 2003).

2. Experimental facilities

The full-scale explosion tests were conducted in the LLEM, which is shown in the plan view of Fig. 1 (Mattes, Bacho, & Wade, 1983; Triebsch & Sapko, 1990). This is a former limestone mine, and five new drifts (horizontal passageways in a mine) were developed to simulate the geometries of modern USA coal mines. The mine has four parallel drifts—A–D. D-drift is a 490 m (1600 ft) long single entry that can be separated from E-drift by an explosion-proof bulkhead door. In order to simulate room and pillar workings, drifts A–C can be used. These three drifts are approximately 490 m (1600 ft) long, with seven crosscuts at the inby end. Drifts C and D are connected by E-drift, a 152 m (500 ft) long entry which simulates a longwall face. Explosion tests can be conducted in the single entry D-drift, the multiple entry area of A-, B-, and C-drifts, or various other configurations including the longwall E-drift. The entries are about 6 m (20 ft) wide by about 2 m (6.5 ft) high, with cross-sectional areas of 12–13 m^2 (130–140 ft^2). The LLEM is designed to withstand explosion pressures of 7 bar or 700 kPa (100 psi). Previous publications described the LLEM coal dust explosion test procedures and the results of LLEM explosion research other than post-explosion observations (Cashdollar, Weiss, Greninger, & Chatrathi, 1992; Sapko, Weiss, Cashdollar, & Zlochower, 2000; Weiss, Greninger, & Sapko, 1989).

Each LLEM drift has 10 data-gathering (DG) stations inset in the rib wall at the locations shown in Fig. 1. Each DG station houses a strain gauge transducer to measure the explosion pressure, and an optical sensor to detect the flame arrival. The wall pressure is perpendicular to the gas flow and is the pressure that is exerted in all directions. This omni-directional pressure is called the "static pressure" by Nagy (1981, p. 58) to differentiate it from the dynamic pressure, although the "static pressure" does vary with time during the explosion. The dynamic or wind pressure is directional. The total pressure is the sum of the omni-directional pressure and the wind or dynamic pressure. Other instruments such as dynamic pressure sensors, heat flux gauges to measure explosion temperatures, optical probes to measure dust dispersion, and movie or video cameras may be installed at various locations in the LLEM. Post-explosion dust sampling was part of the research effort. The dust samples were usually collected from a known area (0.37 m^2 or 4.0 ft^2) on the floor at various distances from the face (closed end of the LLEM drift). A square wooden form was used to define the area. If insufficient dust was collected from a single square, multiple squares were collected. In some cases, band samples were collected. Band samples include dust from a 15 cm (0.5 ft) wide strip along the floor, ribs (walls), and roof. In the standard MSHA band sampling technique, the

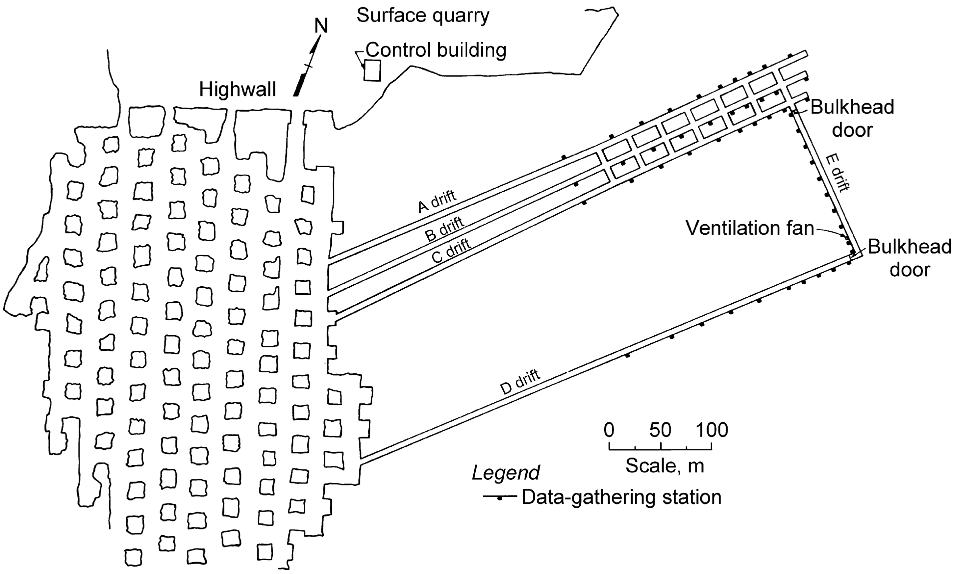

Fig. 1. Plan view of the Lake Lynn Experimental Mine (LLEM).

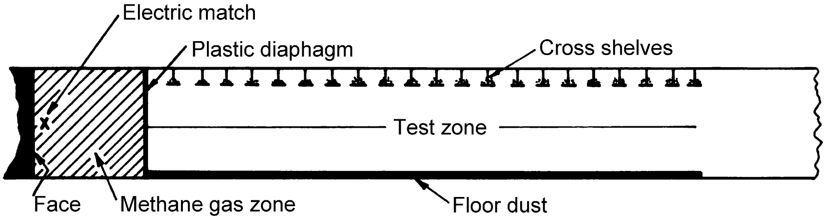

Fig. 2. Side view of D-drift in the LLEM, showing gas ignition zone and dust test zone (not to scale).

floor samples are collected to a depth of 1 in. The dust layer depth after the LLEM explosions was much less than 1 in, and therefore all the dust was collected. Most of the LLEM dust explosion tests described in this paper were conducted in the single entry D-drift, which was isolated from the E-drift by means of the explosion-proof movable bulkhead door (Fig. 1). The ignition zone for a typical D-drift dust explosion test (Fig. 2) was a methane–air mixture at the face (closed end). This methane–air zone was ignited by electric matches. In tests involving pure fuel (coal dust), all the dust was placed on roof shelves to enhance the dispersion. In the rock dust inerting tests, the coal dust and limestone rock dust mixture was placed half on roof shelves and half on the floor. The nominal dust loading reported for the LLEM tests assumes that all the dust was dispersed uniformly throughout the cross section. For the LLEM tests, D-drift was thoroughly washed down several days before the test to allow the entry to dry before the day of the test. In addition, the access ramp at the open end of the drift was wetted down on the day of the test. The purpose was to significantly minimize contamination of the post-explosion dust samples.

Dust explosion research was also conducted in the Fike Corporation 1 m^3 (1000 L or 35 ft^3) chamber (Cashdollar & Chatrathi, 1993; Going, Chatrathi, & Cashdollar, 2000) shown in Fig. 3. The chamber is spherical with an internal diameter of 1.22 m (4.0 ft) and a pressure rating of 21 bar. The two halves of the sphere are connected by twelve 51 mm diameter bolts. Two variable reluctance pressure transducers were used to measure the explosion pressure. PRL-designed optical dust probes (Cashdollar, Liebman, & Conti, 1981; Liebman, Conti, & Cashdollar, 1977) monitored the dust dispersion. Data from the instruments were collected by a high-speed PC-based data acquisition system. The dust injection system for the 1 m^3 chamber consisted of a 5 L dispersion reservoir, a 19 mm pneumatically activated ball valve, and a rebound nozzle. To create a dust cloud, a weighed sample of dust was placed in the dispersion reservoir. The reservoir was pressurized with dry air to a gauge pressure of 20 bar g. The chamber was partially evacuated to an absolute pressure of 0.88 bar a. Activation of the ball valve dispersed the dust and air into the 1 m^3 chamber through the rebound nozzle and raised the chamber pressure to about 1 bar a. The ignitor was activated 0.6 s after activation of the ball valve. The ignition sources used for the tests were 5 and 10 kJ pyrotechnic ignitors manufactured by Fr. Sobbe[1] of Germany. They were activated electrically with an internal fuse wire and delivered their energy in about 10–20 ms. The 5 kJ ignitor by itself produced a pressure rise of 0.02 bar in the 1 m^3 chamber. For higher ignition energies, multiple 10 kJ ignitors were used. All of the ignitors were positioned at the center of the chamber and were pointed down toward the bottom of the 1 m^3 chamber. The chamber was thoroughly cleaned before each test so that there would be no contamination from residue from previous tests. After the explosion test, all of the walls were brushed down to collect as much of the post-explosion dust sample as possible. A few laboratory tests were conducted in the NIOSH-PRL 20 L chamber (Cashdollar, 1996; Cashdollar & Hertzberg, 1982). The test procedures and instrumentation for the 20 L chamber were similar to those of the 1 m^3 chamber.

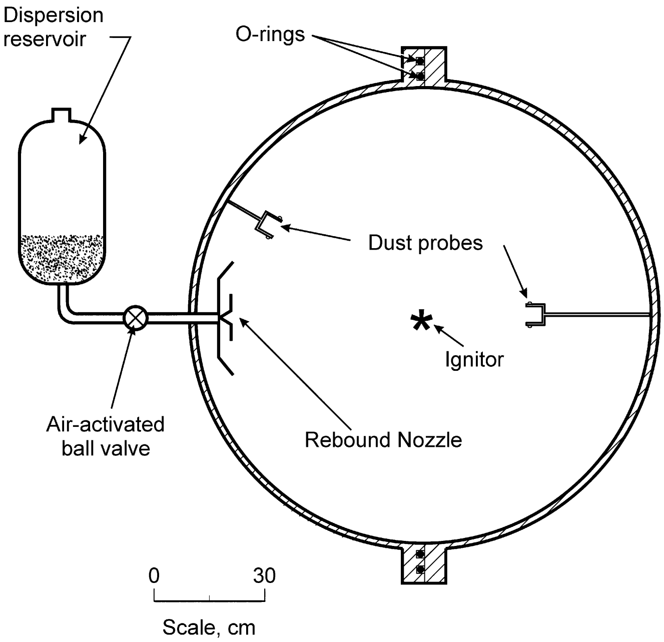

Fig. 3. Fike 1 m^3 explosion test chamber.

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[1] Mention of any company or product does not constitute endorsement by NIOSH.

3. Post-explosion dust analysis procedures

The low temperature ashing (LTA) measured the incombustible content of the dust samples, including the ash in the coal plus the limestone rock dust. The LTA analyses were conducted at both the NIOSH-PRL at Pittsburgh, PA, and at the MSHA laboratory at Mt. Hope, WV. First, all the dust samples were sieved minus 20 mesh (850 μm). The LTA was conducted for both 4 and 24 h at 515 °C on most of the samples. The 515 °C temperature is intended to burn up all the coal, but not to decompose the limestone rock dust ($CaCO_3$). In order to test this, a 24 h LTA was run on limestone rock dust and the recovery was greater than 99%. The 4 h procedure is the standard one MSHA uses for routine mine dust samples for compliance with rock dusting regulations. The 24 h procedure was first used at PRL after the 4 h procedure did not appear to burn up all the coal or char in post-explosion samples. The comparison data are presented in the next section on "Observations and Data." There was a slight difference in the procedures for the "4 h" LTA at the two labs. MSHA used separate samples for the 4 and 24 h LTA. PRL heated the samples for 4 h, weighed them, and then re-heated them for an additional 20 h. The MSHA "4 h" procedure was a 1.5 h ramp-up and 2.5 h at 515 °C for a total of 4 h heating. The PRL "4 h" procedure was a 1.3 h ramp-up and 4 h at 515 °C. These differences in NIOSH-PRL and MSHA ashing procedures were not discovered until after the samples had been analyzed. In addition, at PRL, the dust samples were desiccated before the LTA, so that the incombustible content would be on a dry basis. At MSHA, the moisture was separately measured by heating the coal at 105 °C before the LTA analysis.

The alcohol coking analyses were conducted at the MSHA laboratory at Mt. Hope, WV. For this analysis, approximately 1 g of the −20 mesh post-explosion residue was placed in a test tube 2.5 cm in diameter. Approximately 15 mL of denatured ethyl alcohol was added, and the sample was stirred to ensure that all the particles were wetted. Then the sides of the test tube were washed down with approximately 5 mL of alcohol, and the liquid was allowed to rest for about 5 min. This ensured that all particles that were more dense than the alcohol would settle to the bottom. The sample was then classified based on the amount of coked material that was observed floating on the surface of the alcohol. The classifications are based on the reference chart in Fig. 4. This alcohol coking test measures the amount of material whose density is less than that of the alcohol. Coal, which has a density of ~1.3 g/cm^3, sinks in the alcohol, which has a density of 0.8 g/cm^3. The coke consists of those particles that float.

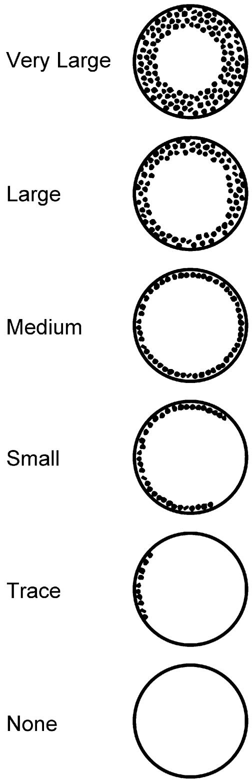

Fig. 4. Qualitative alcohol coke test observations.

4. Observations and data

Figs. 5–7 show data from dust explosion test #471 at the LLEM in February 2004. The dust was dispersed and ignited by an 8.2 m (27 ft) long zone of 10% methane in air at the face of D-drift (Fig. 2). A mixture of 35% coal dust and 65% limestone rock dust was placed on the floor and on shelves from 8.2 to 62.5 m (27 to 205 ft) from the face. The coal dust was Pittsburgh seam high-volatile bituminous coal that had been pulverized to ~73% minus 200 mesh (75 μm). A second dust zone of 20% coal dust and 80% rock dust was on the floor and on shelves from 62.5 to 135.6 m (205 to 445 ft) from the face. In both dusted zones, the coal dust concentration was 150 g/m^3. Fig. 5 shows the maximum pressure versus distance in D-drift during the explosion. The pressure reached a maximum of 76 kPa (11 psi) at 30 m (100 ft) from the face. The pressure decreased gradually to 49 kPa (7 psi) at a distance of 229 m (750 ft). The flame sensors showed significant flame out to 105 m (346 ft). There were small but measurable signals on the flame sensors from 119 to 153 m (390 to 501 ft). These small signals probably corresponded to either localized burning or to post-combustion hot particles that were gradually cooling as they were carried out of the drift by the expanding gases. There were no signals on the flame sensors beyond 153 m. The flame sensor data showed that the dust flame propagated rapidly through the coal and 65% rock dust mixture. When it reached the 80% rock dust zone at 62.5 m, the flame slowed and then died at about 110 m (360 ft). This was expected since previous experimental mine tests had shown that an explosion of this size of bituminous coal dust will not propagate through a mixture with 80% rock dust (Nagy, 1981; Sapko et al., 2000).

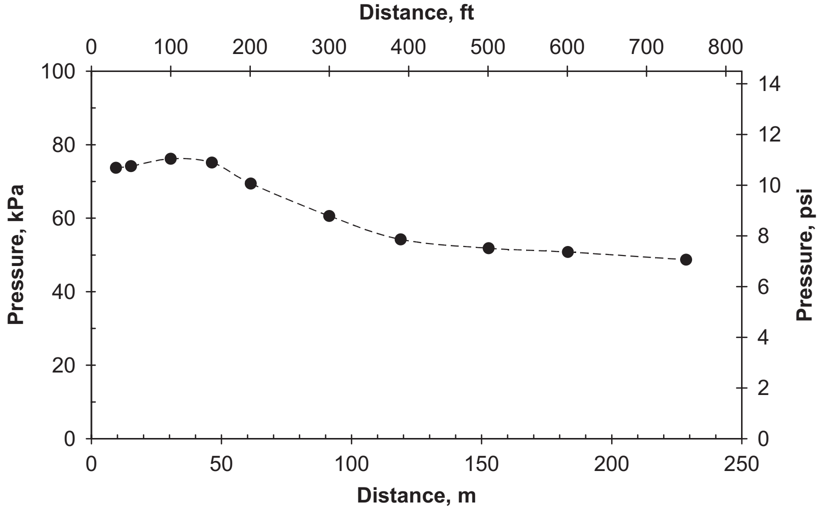

Fig. 5. Explosion pressures versus distance during test #471 in D-drift at the LLEM.

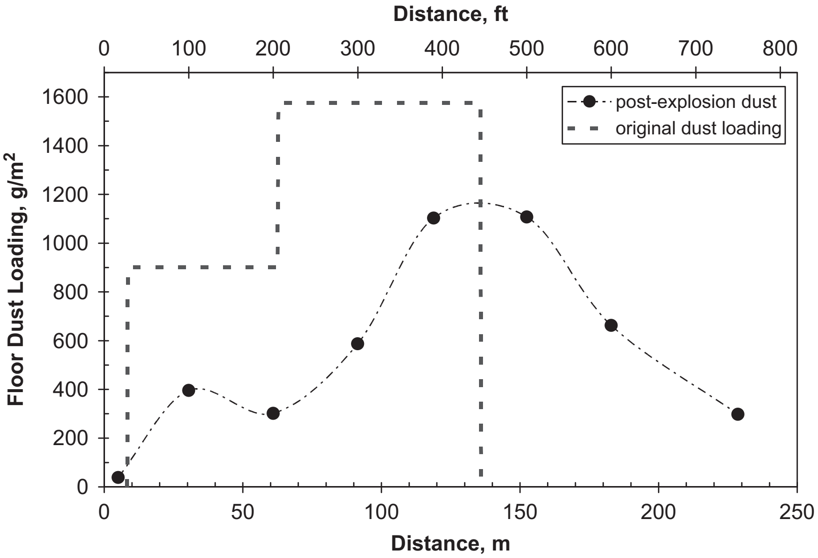

Fig. 6. Dust loading before and after LLEM explosion test #471.

After the explosion test in the LLEM, dust samples were collected from the mine floor at various distances from the face and then sieved minus 20 mesh (850 μm). The calculated dust loadings in g/m^2 before and after the explosion are shown in Fig. 6. The dust loading before the explosion includes the 150 g/m^3 of coal dust and 279 g/m^3 of rock dust for a total 429 g/m^3 of dust from 8.2 to 62.5 m. Based on the average height of D-drift of 2.1 m (6.9 ft), the calculated nominal floor loading was 900 g/m^2. This calculation includes both the dust on the floor and on the shelves. The zone from 62.5 to 135.6 m had 20% coal and 80% rock dust for a calculated floor loading of 1580 g/m^2. These pre-explosion dust loadings are shown by the heavy dashed line in Fig. 6. The post-explosion dust loadings were calculated from the amount of dust collected from measured areas at various locations. These data are shown as the solid circle data points in Fig. 6. It is obvious from the figure that, after the dust is dispersed, it is carried some distance by the dynamic pressure or wind of the explosion. The pre-explosion dust loading stopped at 135.6 m (445 ft) from the face. After the explosion, significant amounts of dust were collected at distances up to 229 m (750 ft). A more violent explosion may carry the dust even farther.

The incombustible contents (measured by LTA) before and after the explosion are shown in Fig. 7. The original incombustible amounts are shown as the heavy dashed line. It shows the original 67% incombustible (from the 65% rock dust and the additional 2% from the ash in the coal fraction of the total dust mix) from 8.2 to 62.5 m (27 to 205 ft). The original 81% incombustible zone extended from 62.5 to 135.6 m (205 to 445 ft). The post-explosion samples are shown by the solid circle data points. In the region that had an original incombustible content of 67%, the post-explosion incombustible was ~80%. This shows

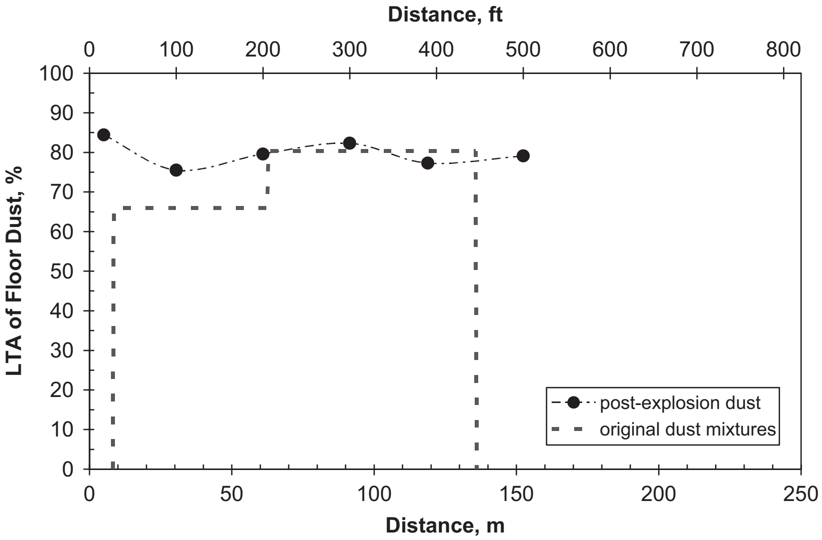

Fig. 7. Incombustible content before and after LLEM explosion test #471.

that a significant amount of the coal in this region was burned during the explosion. The incombustible content further from the face was also ~80%, similar to the original pre-explosion content in this zone. Since the explosion flame stopped at ~110 m (360 ft), the dust collected beyond that distance would be mainly dust that had been dispersed, but had not been in the explosion flame. Therefore, the post-explosion incombustible content of this dust should be essentially the same as the original pre-explosion incombustible content. For the post-explosion LTA data, only samples collected within the dusted zone or slightly beyond were included in Fig. 7. Since smaller amounts of dust were collected far beyond the dusted zone, there would be an increased possibility of contamination from any small amounts of limestone dust that would come from the roof and ribs of the limestone mine during the dust explosion test.

The data shown in Figs. 5–7 are examples of the type of data collected for the various LLEM dust explosion tests. Post-explosion dust samples from other LLEM dust explosions from 1999 through 2004 were also collected and then analyzed at NIOSH–PRL and MSHA. For the post-explosion incombustible analyses, only samples collected within the dusted zone or up to 30 m (100 ft) beyond were included in the data summary.

Post-explosion dust samples were collected from both the experimental mine and laboratory experiments to compare the pre- and post-explosion incombustible contents and the coke amounts. The 1 m^3 data included tests with pure coal dusts and with various mixtures containing 30–65% limestone rock dust. The coal dusts included both the high-volatile Pittsburgh seam bituminous and low-volatile Pocahontas seam bituminous. The LLEM data were for Pittsburgh high-volatile coal dust with 65–80% rock dust in the mixture. Most of the tests were with pulverized coal with ~73% minus 200 mesh (75 μm), but one test was with an even finer size of coal and one was with a coarse size of coal. The volatility and size data for the coals tested are in Table 1. The size data are from a combination of sonic sieving and Coulter Counter analyses. The percentage minus 200 mesh is listed in column three. The next two columns list the surface and mass (volume) weighted mean diameters. The last column lists the mass median diameter. The size data for the limestone rock dust are listed in the last line of the table.

The summary post-explosion LTA data from NIOSH–PRL and MSHA are shown in Figs. 8–10. Fig. 8 compares the measured ash or incombustible content from 4 h versus 24 h LTA for post-explosion samples from Fike 1 m^3 chamber tests and a few samples from LLEM tests. The data include samples from tests with Pittsburgh (Pgh) coal, Pocahontas (Poc) coal, and mixtures of coal and rock dust. Each data point compares the results of both 4 and 24 h LTA analyses for a single sample. Data points along the dotted line in Fig. 8 represent perfect agreement between the 4 and 24 h analysis procedures. For 1 m^3 tests with pure Pocahontas coal (no rock dust), the 4 h LTA gave an incombustible content of 19–29%. The 24 h LTA gave a result of 8–12% post-explosion incombustible. It appears that not all of the coal and char was combusted during the 4 h LTA for the low-volatile Pocahontas coal samples. The longer 24 h LTA burned all of the coal/char and gave a more accurate result. There was less of a difference in the 4 and 24 h data for the high-volatile Pittsburgh coal samples. There is little difference in the 4 and 24 h data at high (60–80%) LTA values for either the 1 m^3 laboratory chamber samples or the LLEM samples. In conclusion, the data show that the 24 h LTA is better than the 4 h LTA for post-explosion samples with low incombustible content.

A comparison of the pre-explosion and post-explosion incombustible contents is shown in Fig. 9, which includes NIOSH-PRL and MSHA data for samples from both the LLEM and the Fike 1 m^3 laboratory chamber.

Table 1
Analyses of the bituminous coal dusts and rock dust

	Volatility (%)	−200 mesh (%)	D_S (μm)	D_W (μm)	D_{med} (μm)
Fine Pittsburgh	36	100	9	14	11
Pulverized Pittsburgh (PPC)	36	73	34	58	56
Coarse Pittsburgh	36	~10	~170	~620	~690
Pulverized Pocahontas	17	86	17	41	27
Limestone rock dust	–	73	16	50	~35

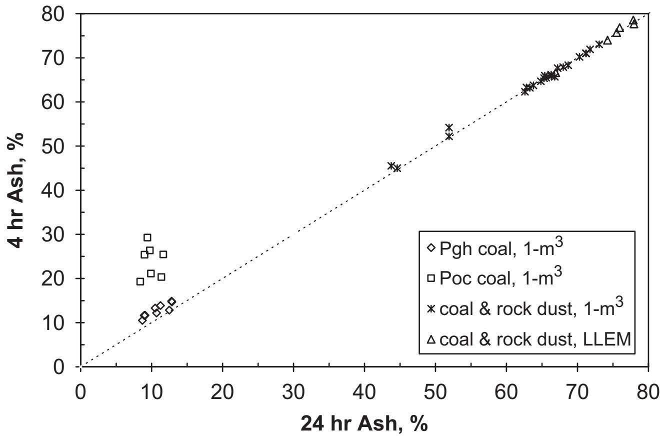

Fig. 8. Comparison of 4-h versus 24-h incombustible contents for post-explosion samples from tests in the Fike 1 m^3 laboratory chamber and the LLEM.

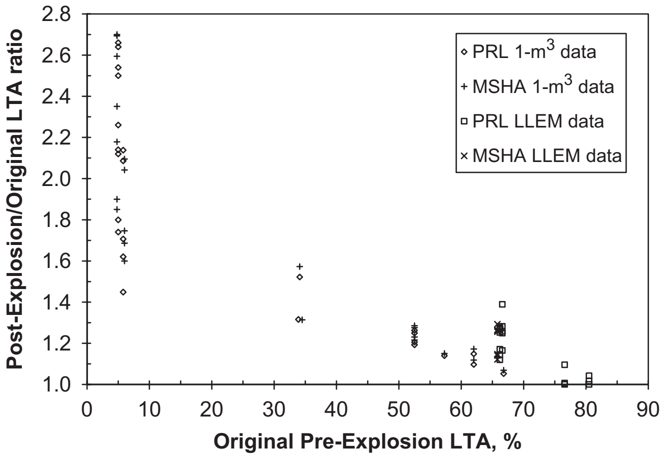

Fig. 10. Post-explosion to pre-explosion incombustible ratio from tests in the LLEM and the Fike 1 m^3 laboratory chamber.

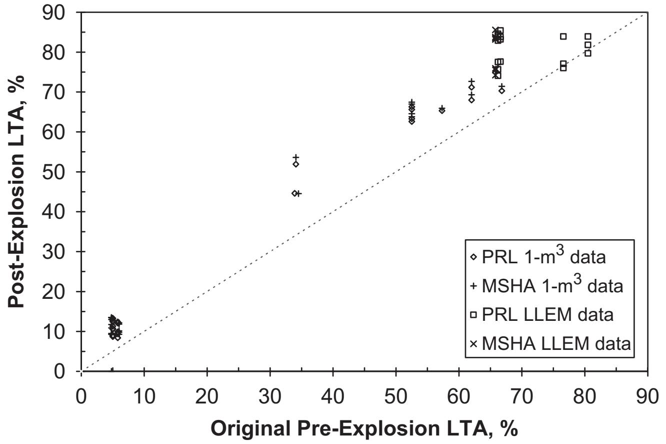

Fig. 9. Comparison of pre-explosion versus post-explosion incombustible contents from tests in the LLEM and the Fike 1 m^3 laboratory chamber.

The incombustible content includes the rock dust plus the ash in the coal. It was measured by low-temperature ashing of the post-explosion residue for 24 h at 515 °C. (For this comparison and the other figures, the incombustible did not include the MSHA moisture content, which was ~1% for these samples.) The dotted line would represent no change in the incombustible content from pre-explosion to post-explosion samples. The conclusion is that the post-explosion incombustible content was always as high as or higher than the initial incombustible content. This conclusion is similar to that previously reported by Nagy and Mitchell (1963) based on very limited data from early experimental mine explosions.

The pre-explosion versus post-explosion data comparison is shown in a different way in Fig. 10. In this graph, the ratio of post-explosion to original incombustible content is plotted as a function of the original or pre-explosion incombustible content as measured by LTA. This shows that the largest change in incombustible content occurs at the lowest incombustible content. On average, the post-explosion ash is about twice the original ash content for the tests with pure coal dust (no rock dust). This means that about half of the coal is burned during these explosions. For tests with high original incombustible contents, even if half of the coal were burned, the post-explosion incombustible content would not increase greatly because the coal is only a small fraction of the total dust content.

All of the alcohol coking analyses were conducted by the MSHA laboratory at Mt. Hope, WV. Table 2 is a summary of the coking data for samples from LLEM explosion tests. All of these analyses were conducted “blind,” with the MSHA laboratory not knowing the type of LLEM explosion test or the extent of flame travel. The LLEM test number and date are listed in the heading for the data set for each LLEM test. All of the post-explosion samples were collected from the floor, except for those listed as

Table 2
Alcohol coke amounts at various distances for post-explosion dust samples

Distance (ft)	2003	2004	Distance (ft)	2003	2004	Distance (ft)	2003	2004
LLEM #386, 8 Sept 1999			LLEM #388, 23 Sept 1999			LLEM #389, 4 Nov 1999		
152	Large	Large	100	None	Small	108	–	Large
300	Small	Small	201	None	Small	211	–	Large
390	Trace	Trace	300	None	Trace	329	–	Large
501	None	None	390	None	None			
PPC and 77% rock dust to D-310 ft, flame to 310 ft			Pgh Fines and 77% rock dust to D-310 ft, flame to 340 ft			PPC and 65% rock dust to B-340 ft, flame to 530 ft		
LLEM #390, 7 Dec 1999			LLEM #398, 1 March 2001			LLEM #400, 20 March 2001		
108	–	Large	100	Large	–	–	–	–
211	–	Large	300	Large	–	–	–	–
329	–	Large	390	Large	–	300	–	Large
–			501	Large	Large	390	–	Medium
626		Small	601	Large	Medium	501	–	Small
			750	Small	Small			
PPC and 65% rock dust to B-460 ft, flame to 830 ft			PPC and 65% rock dust to D-460 ft, flame to 1250 ft			PPC to D-250 ft, no rock dust, flame to 640 ft		
LLEM #401, 28 March 2001			LLEM #434, 25 March 2003			LLEM #434, 25 March 2003		
100	Large	V. large	134	V. large	–	Band samples		
201	Large	Large	234	V. large	–	234	V. large	–
300	Trace	Trace	304	V. large	–	304	V. large	–
390	None	None	403	V. large	–	403	V. large	–
501	None	None	501	V. large	–	501	V. large	–
601	Trace	Trace	598	V. large	–	–	–	–
750	Small	Trace	757	Trace	–	–	–	–
PPC and 80% rock dust to D-460 ft, flame to 200 ft			PPC and 65% rock dust to C-310 ft, flame to 770 ft			PPC and 65% rock dust to C-310 ft, flame to 770 ft		
LLEM #471, 26 Feb 2004			LLEM #473, 11 March 2004			LLEM #474, 18 March 2004		
100	–	V. large	16	–	Large	100	–	V. large
201	–	V. large	100	–	Large	201	–	V. large
300	–	Large	201	–	Small	300	–	Large
390	–	Small	300	–	None	390	–	Trace
501	–	Trace	390	–	None			
601	–	Trace						
PPC and 65% rock dust to 205 ft, PPC and 80% rock dust, 205–445 ft, flame to ~360 ft			PPC and 65% rock dust to D-250 ft, flame to 220 ft, explosion failed to propagate because of weak ignition zone			coarse Pgh coal and 50% rock dust to D-250 ft, flame to 310 ft		

"band samples" for test #434. The amounts of coke (observed using the alcohol coking test) are listed for samples at various distances from the LLEM face. For some of the samples, duplicate analyses were conducted in 2003 and 2004. Below each data set, the dust mixture and location are listed. For example, in test #386, "PPC and 77% rock dust to D-310 ft" means that a mixture of 23% Pittsburgh pulverized coal (PPC) and 77% limestone rock dust was loaded in the LLEM out to a distance of 310 ft in D-drift. For this test, the flame propagated to a distance of about 310 ft from the face. The "Pgh fines" listed for test #388 and the "coarse Pgh coal" listed for test #474 refer to the two other sizes of Pittsburgh coal dust listed in Table 1. In general, "large" or "very large" amounts of coke were observed in samples within the flame zone for the LLEM tests. Beyond the end of the flame, the coke observations were only "small," "trace," or "none." At the location where the flame ended, there was a large variation in observed coke amounts—from "small" to "large." This is not surprising since the explosion flame dies out gradually and the listed flame travel distance is uncertain by about ±10 m or ±30 ft. In general, there was good reproducibility in the coke analyses from 2003 and 2004 even though the alcohol coking test is somewhat subjective.

There were a few exceptions in the coke observations. In test #390, there was only a small amount of coke in the sample from 626 ft, even though the flame went to 830 ft. In test #398, there was only a small amount of coke in the sample from 750 ft, even though the flame went to 1250 ft. However, in both of these cases, the samples were from far beyond the original dusted zone and the floor samples may have contained only small amounts of dust. The other significant exception is test #388, where the flame traveled to 340 ft, but the coke observations were small, trace or none. The difference in this LLEM test was that the coal dust was very fine in size. It is possible that the finest sizes of coal dust do not generate significant amounts of coke particles when they burn, at least as measured by the alcohol coking test.

The fact that large and very large amounts of coke were observed within the flame zones for LLEM tests with initial rock dust contents up to 65%, 77% and even 80% was initially somewhat surprising. Nagy and Mitchell (1963, p. 2) had said that "coke is not formed where the dust contains more than 50% incombustible," based on observations after earlier Bruceton Experimental Mine tests. However, they did not identify how the coke amount was determined in their studies. Based on their other comments about coke and the references to photos in their report, it is possible that their coke amounts were based on visual observations only. It is likely that the alcohol coking test is more sensitive in detecting evidence of coke than visual observations would be.

Krzystolik and Lebecki (1983) also observed coke after explosions at the Polish Experimental Mine Barbara. They used an optical microscope to observe the percentage of coke particles in the dust samples. All of their tests were for pure coal dust, without any rock dust. They concluded that the presence of coked particles could be used to estimate the flame range in most cases. This is consistent with the results of the present PRL data.

During LLEM gas explosion tests #484 and #485 in 2005, small trays of pulverized and coarse Pittsburgh coal dust were placed on the floor near the face in the methane gas ignition zone. Although these trays were within the gas flame zone, the dust was not dispersed because the dynamic or wind pressure was very low near the origin of the explosion. Samples were collected from these trays after the explosion and only trace amounts of coke were found. This shows that the coal dust must be dispersed into the flame before large amounts of coke are generated.

In a series of laboratory experiments in the PRL 20-L chamber in 2005, coal dust of various sizes was dispersed into methane gas explosions. These explosions were ignited by an electric spark. In almost all the tests, large or very large amounts of coke were observed in dust samples collected after the tests. Even 30 × 20 mesh (600–850 μm) Pittsburgh coal showed large amounts of coke. Only the 20 × 10 mesh (850–1200 μm) Pittsburgh coal showed a small amount of coke. This shows that even very large coal particles up to 20 mesh (850 μm) become coked when they are in a flame, even though this size of coal is too large to propagate an explosion in the absence of methane.

5. Conclusions

The experimental mine and laboratory data show that the post-explosion incombustible content is as high as or higher than the pre-explosion incombustible content for both high-and low-volatile coals. The data from the alcohol coking test show that coke is almost always found whenever coal particles are dispersed into a flame, and therefore the presence of coke is a good indication of the extent of flame travel. Coke, as measured by the alcohol coking test, is found after explosions at rock dust contents even up to 80%. The results of this joint research will assist MSHA in their future investigations of coal mine explosions.

Disclaimer: The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health or the Mine Safety and Health Administration.

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