Experimental mine and laboratory dust explosion research at NIOSH

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Abstract

This paper describes dust explosion research conducted in an experimental mine and in a 20-L laboratory chamber at the Pittsburgh Research Laboratory (PRL) of the National Institute for Occupational Safety and Health (NIOSH). The primary purpose of this research is to improve safety in mining, but the data are also useful to other industries that manufacture, process, or use combustible dusts. Explosion characteristics such as the minimum explosible concentration and the rock dust inerting requirements were measured for various combustible dusts from the mining industries. These dusts included bituminous coals, gilsonite, oil shales, and sulfide ores. The full-scale tests were conducted in the Lake Lynn experimental mine of NIOSH. The mine tests were initiated by a methane–air explosion at the face (closed end) that both entrained and ignited the dust. The laboratory-scale tests were conducted in the 20-L chamber using ignitors of various energies. One purpose of the laboratory and mine comparison is to determine the conditions under which the laboratory tests best simulate the full-scale tests. The results of this research showed relatively good agreement between the laboratory and the large-scale tests in determining explosion limits. Full-scale experiments in the experimental mine were also conducted to evaluate the explosion resistance characteristics of seals that are used to separate non-ventilated, inactive workings from active workings of a mine. Results of these explosion tests show significant increases in explosion overpressure due to added coal dust and indications of pressure piling.

Keywords: Explosion; Mining; Flame propagation; Deflagration

1. Introduction

There has been a notable decline in the frequency and severity of mine explosions since the early part of the twentieth century. Among the major safety measures responsible for this decline are the use of general rock dusting, development of permissible explosives and electrical equipment, improved ventilation, and improved methods for detecting hazardous conditions. Although these advances in mine safety are noteworthy, the problem of mine explosion prevention is not completely solved, for serious mine explosions still occur (Sapko, Greninger & Watson, 1989; Dobroski, Stephan & Conti, 1996). For many mines, the almost continual deposition of fine-sized float coal dust on the floor, ribs, and roof of mine entries and returns, coupled with the intermittent application of rock dust, has resulted in stratified layers of dust (Sapko, Weiss & Watson, 1987a). Over the years, changes in mining technology have produced increased amounts of finer float coal dust, which has compounded safety matters (Sapko, Weiss & Watson, 1987a). Frictional ignitions of methane are also a serious concern, and their potential for disastrous consequences is well known.

Much knowledge has been obtained from the full-scale explosion research conducted by mine safety research establishments during the past two decades (Sapko et al., 1989, 1987a; Weiss, Greninger & Sapko, 1989; Cashdollar, Sapko, Weiss & Hertzberg, 1987; Nagy, 1981; Michelis, Margenburg, Müller & Kleine, 1987; Reeh & Michelis, 1989; Sobala, 1987; Cashdollar, Weiss, Greninger & Chatrathi, 1992; Greninger, Cashdollar, Weiss & Sapko, 1990; Sapko, Weiss & Watson, 1987b; Lebecki, 1991; Michelis, 1996). This research has provided important practical data and a better understanding of the fundamental explosion processes. Previous Pittsburgh Research Laboratory[1] (PRL) experi-

[1] The Pittsburgh Research Laboratory was part of the U.S. Bureau of Mines before its transfer to the National Institute for Occupational Safety and Health (NIOSH) in October 1996.

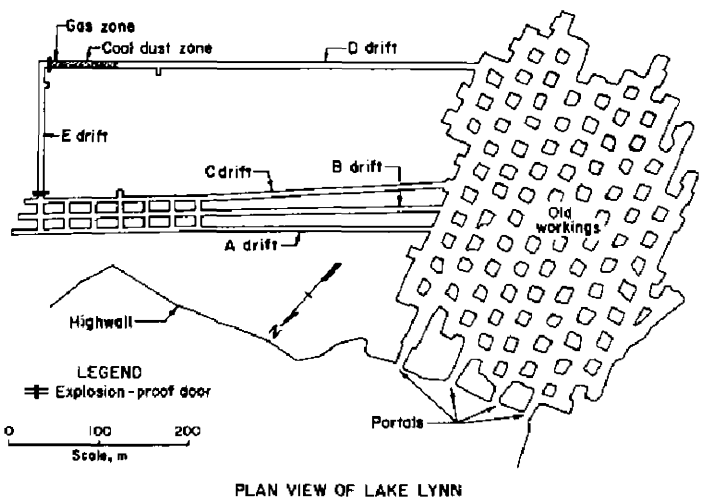

Fig. 1. Plan view of the Lake Lynn experimental mine.

mental mine research has included studies of float coal dust hazards (Sapko et al., 1989), minimum explosible coal dust concentrations (Weiss et al., 1989; Cashdollar et al., 1987, 1992; Greninger et al., 1990), rock dust inerting requirements (Weiss et al., 1989; Cashdollar et al., 1987, 1992; Greninger et al., 1990), the effects of pulverized versus coarse coal particle size (Weiss et al., 1989), and secondary explosion hazards associated with oil shale and sulfide ore dusts (Weiss, Cashdollar, Sapko & Bazala, 1996).

The present publication provides data on the effect of volatile matter on the explosibility of fuel dusts such as coals and gilsonite. Included are data on the minimum explosible concentration (MEC) and the amount of limestone rock dust required to inert the fuel dusts. The data from full-scale experimental mine and laboratory tests are also compared to thermodynamic model calculations. Some of these experimental data[2] were presented previously (Greninger et al., 1990). Also included are explosion propagation data from full-scale gas and dust explosions that were used to evaluate the explosion resistance characteristics of seals that are used to isolate unused (gob) areas of mines.

2. Experimental facilities and test procedures

The full-scale explosion tests were conducted in PRL's Lake Lynn experimental mine (Mattes, Bacho & Wade, 1983; Triebsch & Sapko, 1990) (LLEM) shown in Fig. 1. This is a former limestone mine, and five new drifts were developed to simulate the geometries of modern US coal mines. The mine has four parallel drifts — A, B, C, and D. Drifts C and D are connected by E-drift, a 152-m long entry which simulates a longwall face. Most of the dust explosion tests described in this paper were conducted in the single entry D-drift, which was isolated from E-drift by means of an explosion-proof movable bulkhead door (Fig. 1). D-drift is 520 m long with a cross-sectional area ranging from 11.2 to 13.0 m^2 (average 12.8 m^2). The average height in D-drift is 2.1 m and the average width is 6.0 m. The D-drift face (closed end) is formed by the closed bulkhead door. D-drift was instrumented (Fig. 2) with pressure transducers located at the face and at 10, 15, 31, 46, 61, 91, 119, 153, 183, and 229 m from the face. Optical flame sensors were located at 5, 10, 15, 23, 31, 38, 46, 53, 61, 76, 91, 105, 119, 136, 153, 168, 183, 198, 213, and 229 m from the face.

The ignitor for all of these D-drift dust explosibility tests was a 12-m long zone of a 10% methane in air mixture at the face (closed end). This 152-m^3 methane–air zone was ignited near the center of the face using electric matches grouped in a single-point configuration. In tests involving pure fuel (gilsonite or coal) dust, all the dust was placed on roof shelves to enhance the dispersion. In the rock dust inerting tests, the fuel dust and limestone rock dust mixtures were placed half on roof shelves and half on the floor (Fig. 2). The nominal dust loading reported for the LLEM tests assumes that all of the dust was dispersed uniformly throughout the cross section. The D-drift dust test zone extended from the end of the methane zone (12 m) out to 76, 94, 152, or 195 m from the face. The length of the total test zone listed in the remainder of this paper will be the total distance from the face, including the 12-m long methane ignitor zone.

[2] Note that some of the data have been revised slightly from those listed previously, based on a re-analysis of the data.

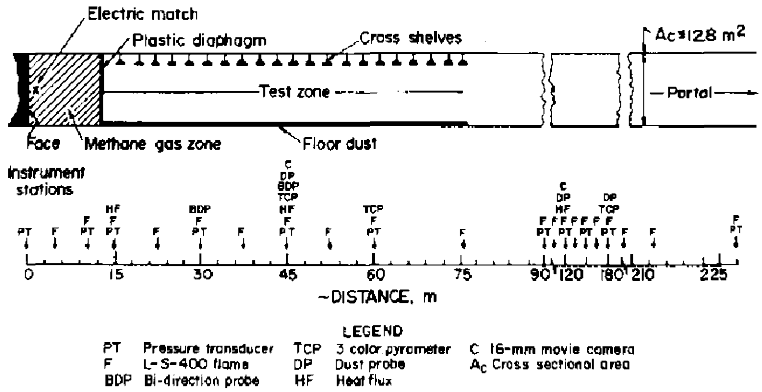

Fig. 2. Side view of D-drift in the Lake Lynn experimental mine, showing instrumentation.

Various explosion resistant seal designs were evaluated through full-scale explosion tests in C-Drift in the LLEM. Fig. 3 shows an expanded view of the seal test area. The seals were constructed in the crosscuts between B- and C-drifts; these crosscuts are approximately 2.0 m high by 5.8 m wide, giving an average cross sectional area of 11.6 m^2. Methane was injected into the closed end of C-drift. A plastic diaphragm was used to contain the 9% CH_4–air mixture within the first 14.3 m of the entry (~190-m^3 zone). Electric matches, located at the face or closed end of the entry, were used to ignite the flammable CH_4-air mixture. Barrels filled with water were located in the gas zone to act as turbulence generators to increase the flame speed and achieve the desired pressure loading. Each data-gathering station in C-drift houses a pressure transducer and optical flame sensor located at distances of 4, 26, 41, 56, 71, 93, 123, 153, 182, and 231 m from the face.

The laboratory data in this paper were collected in the PRL 20-L explosibility test chamber (Cashdollar et al., 1987, 1992; Cashdollar & Hertzberg, 1985) shown in Fig. 4. The test procedure includes the partial evacuation of the chamber and the dispersion of the dust by a blast of air from the bottom. The ignition source is energized after the pressure has returned to about 1 atm or 1 bar absolute and the dust has been uniformly dispersed. The ignition sources were strong chemical ignitors with energies of 2500 or 5000 J. The instrumentation for the 20-L chamber includes a pressure transducer and optical dust probes (Cashdollar, Liebman & Conti, 1981; Conti, Cashdollar & Liebman, 1982) for monitoring dust dispersion uniformity. Details of the operating procedures

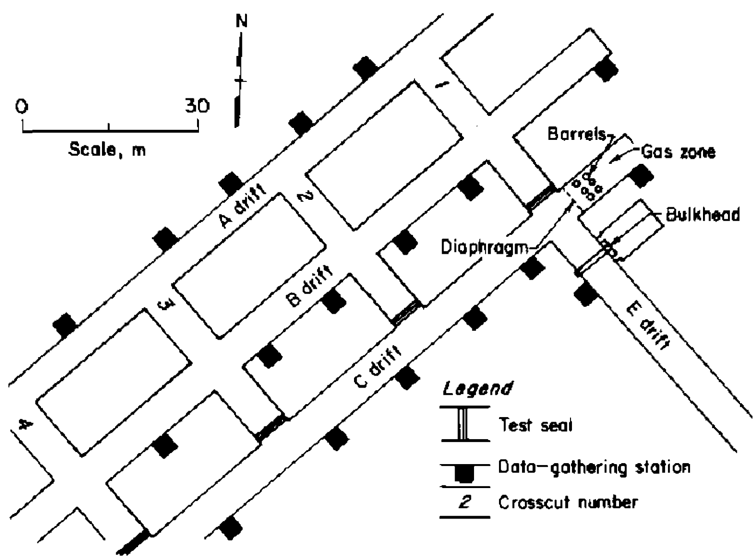

Fig. 3. Diagram of seal test area in LLEM C-Drift.

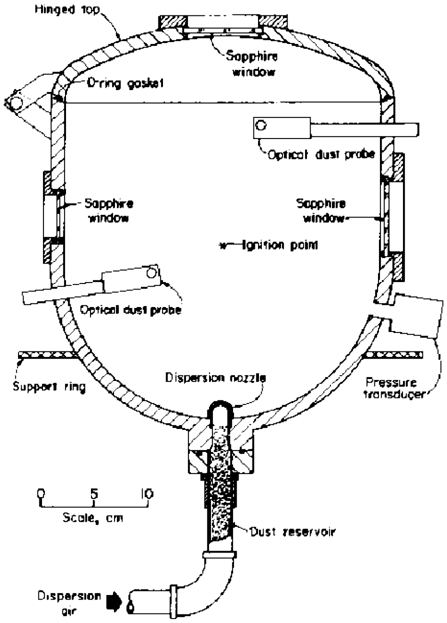

Fig. 4. 20-L laboratory explosibility test chamber.

Table 1
Proximate analyses and heating values for the "as received" Pittsburgh seam bituminous coal and gilsonite

	Pittsburgh coal	Gilsonite
Moisture, %	2	1
Volatile matter, %	36	84
Fixed carbon, %	56	15
Ash, %	6	0
Heating value, cal/g	7700	9900

and dust dispersion uniformity measurements are in Cashdollar et al. (1992), Cashdollar and Hertzberg (1985) and Cashdollar and Chatrathi (1993).

The pulverized coal that was used was Pittsburgh seam high volatile bituminous with a volatility of 36% as measured by ASTM standard test method D3175 (ASTM, 1999). The gilsonite was a natural bitumen or asphaltum that is mined in Utah; it has a volatility of 84%. Additional proximate analysis data and heating values are listed in Table 1. Both fuel dusts were pulverized and had 80–91% by weight minus 200 mesh (<75 μm). Additional size data are listed in Table 2. The gilsonite was finer in size, with 36% less than 20 μm, compared to 15% less than 20 μm for the coal. The surface mean diameter is $\bar{D}_S$, the mass or volume mean diameter is $\bar{D}_W$, and the mass median diameter is D_{med}. In addition to the two fuel dusts, the size analysis data of the limestone rock dust are also listed in Table 2. The particle size data are from a combination of sonic sieve and Coulter Counter data.[3]

3. Single entry explosion studies

In the LLEM D-drift tests, the methane explosion at the face both entrains and ignites the dust. The flame from the methane–air ignition zone travels about 65 m, even in the absence of any fuel dust in the test zone. The ignitor also produces an overpressure of ~1 bar (~100 kPa). For a dust explosibility test, if the flame does not reach the end of the test zone, the result is a nonpropagation (NP). For the shorter test zones (76 or 94 m long), the result is considered a marginal propagation (M) if the flame just reaches the end of the test zone or slightly beyond. If the flame travels more than 30 m beyond the short test zones, the result is considered a propagation (P). For the longer test zones (150, 152, or 195 m), the result is considered a propagation if the flame travels more than 10 m past the end of the test zone. The propagation criterion for these mine tests is, therefore, more stringent for the shorter test zones. Measurement of the flame travel distance is, of course, limited by the number and locations of the flame sensors. For these tests, the flame sensors were located at intervals of about 31 m for test numbers up to 230 and at intervals of about 15 m for tests after test number 234. The estimated flame travel distance is interpolated between flame sensors, based on the strengths of the signals at the sensors.

These propagation criteria are the same as those used in a previous PRL publication (Greninger et al., 1990). They were developed to give a scientific determination of the conditions under which an explosion would continue to propagate beyond the influence of the ignitor. It is understood, however, that even localized burning that

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

Table 2
Particle size distributions for gilsonite, Pittsburgh coal, and limestone rock dusts

Dust	<20 μm, %	<75 μm, %	$\bar{D}_S$, μm	$\bar{D}_W$, μm	D_{med}, μm
Pittsburgh coal	15	80	30	50	44
Gilsonite	36	91	19	37	28
Limestone rock dust	46	75	14	46	25

extends the length of the CH_4 ignitor flame can be a significant hazard.

One of the questions in both the laboratory and mine tests was whether or not a particular ignition source could "overdrive" the system. To evaluate the possibility of overdriving for the LLEM studies, some tests were made with longer (150-, 152-, or 195-m) test zones instead of the 76- or 94-m test zones used for the majority of the tests. These longer zone tests would determine whether the flame continued to propagate beyond any possible influence of the ignitor. In the 20-L laboratory tests, different ignitor strengths were used to evaluate the effect of "overdriving." At some ignitor strength, the ignitor energy and flame volume would become too large for the 20-L chamber. In this situation, the ignitor flame would be sufficient to combust enough dust so that the result appears to be an explosion although there is no real propagation beyond the ignitor flame. The 20-L laboratory data were also compared to data from a much larger 1-m^3 (1000-L) chamber (Cashdollar & Chatrathi, 1993) that would not be "overdriven" by the same ignitor.

The LLEM data for the various dust explosibility tests are listed in Table 3. In the first column is the LLEM test number. In the second column is the total length of the test zone as measured from the face (including both the 12-m methane zone and the dusted zone). The third column lists only the fuel dust part of the nominal loading; it does not include the rock dust part of the coal–rock dust mixtures. The limestone rock dust content of the dust mixture is listed in column four. The total inert or incombustible content of the dust mixture is listed in column five; this includes not only the limestone rock dust but also the ash and moisture in the fuel dust. The ratio of rock dust to fuel dust is listed in the next column. The flame travel distance from the face is listed in column seven. This estimated distance is interpolated between the last flame sensor to detect the flame and the next sensor that does not detect the flame, based on the strengths of the signals at the sensors. The flame travel distance is rounded to the nearest 5 m. The result of the test is listed in the last column, based on the previously described propagation criteria.

3.1. Minimum explosible concentrations

The minimum nominal dust loading for gilsonite in the LLEM was studied using test zones of 94 and 152 m in length. Based on the previously listed flame travel criteria, the 30-g/m^3 loading for the 94-m long test zone (LLEM test 200) was a marginal propagation, but the pressure was very low. With the longer 152-m test zone (LLEM test 236), the 30-g/m^3 test was a nonpropagation. This showed that the flame from the 152-m^3 methane–air ignition zone could overdrive the results somewhat for the minimum loading tests if a short test zone was used. The test results from the longer test zone may be more accurate in the scientific sense, but the results from the shorter test zone are still useful in the practical sense because they are more conservative. At concentrations less than the limit, the fuel dust can still contribute energy and extend the ignitor flame length. At 35 g/m^3, both the tests with the shorter zone (LLEM test 203) and with the longer zone (LLEM tests 235 and 243) propagated beyond the dusted zone. Therefore, the best value for the minimum nominal concentration (lean limit) for flame propagation in the LLEM is about 35 g/m^3 for the gilsonite dust, based on the data from the longer test zone.

For the pulverized Pittsburgh coal (PPC) tests with the 76-m test zone, the 40-g/m^3 dust loading produced a marginal propagation and the 50-g/m^3 loading produced an apparently significant propagation with flame travel out to 135 m. These data were reported previously in Weiss et al. (1989). In later tests with a longer 152-m test zone, a dust loading of 55 g/m^3 failed to propagate to the end of the test zone in LLEM test 239 and almost reached the end of the test zone in test 247. In LLEM test 242, the 60-g/m^3 dust loading propagated well beyond the test zone. Therefore, the best value for the minimum nominal concentration for the Pittsburgh coal dust is about 60 g/m^3, based on the data from the longer test zone. Due to the limited number of mine tests, these minimum concentration data for the gilsonite and coal dusts are rounded to the nearest 5 g/m^3.

Minimum explosible concentrations (lean flammable limits) were also measured in the 20-L laboratory chamber using strong chemical ignitors of 2500- and 5000-J energy (Cashdollar et al., 1992; Cashdollar & Chatrathi, 1993; Cashdollar, Hertzberg & Zlochower, 1989; Cashdollar, 1996). For the gilsonite, the measured minimum explosible concentration was ~35 g/m^3 with the 2500-J ignitor and ~30 g/m^3 with the 5000-J ignitor. For the Pittsburgh coal, the minimum explosible concentration was ~80 g/m^3 with the 2500-J ignitor and ~60 g/m^3 with the 5000-J ignitor. The repeatability of the laboratory MEC data was about ±10%. The question of "overdriving" in laboratory chambers was also investigated by comparing the MEC values from the 20-L chamber with those from a much larger 1-m^3 (1000-L) chamber (Cashdollar & Chatrathi, 1993) at the Fike Corporation in Blue Springs, MO. The minimum explosible concentration for a dust should be that value that is independent of ignition energy. The 1-m^3 MEC data (Cashdollar & Chatrathi, 1993) for each of the two dusts were relatively independent of ignition energy. The MEC for gilsonite was 36 g/m^3 and the MEC for the coal was 80 g/m^3 in the 1-m^3 chamber with a 10-kJ ignitor (Cashdollar & Chatrathi, 1993). This comparison shows that the 5000-J ignitor in the 20-L chamber overdrives the system somewhat for these dusts.

Table 3
Summary of full-scale test results for Pittsburgh coal and gilsonite dusts

LLEM test No.	Test zone, m	Fuel dust loading, g/m³	Limestone rock dust, %	Total inert, %	Rock dust to fuel ratio	Flame travel, m	Result[a]
Pulverized gilsonite dust							
201	94	25	0.0	1	0.0	90	NP
200	94	30	0.0	1	0.0	110	M
236	152	30	0.0	1	0.0	110	NP
203	94	35	0.0	1	0.0	~180	P
235	152	35	0.0	1	0.0	~160	P
243	152	35	0.0	1	0.0	~185	P
202	94	40	0.0	1	0.0	~190	P
229	94	100	79.8	80.0	4.0	~190	P
224	94	100	84.8	85.0	5.6	~190	P
227	94	150	84.8	85.0	5.6	>230	P
217	94	100	89.9	90.0	8.9	75	NP
226	94	150	89.9	90.0	8.9	75	NP
Pulverized Pittsburgh bituminous coal dust							
55	76	30	0.0	8	0.0	75	NP
57	76	40	0.0	8	0.0	100	M
54	76	50	0.0	8	0.0	135	P
239	152	55	0.0	8	0.0	110	NP
247	152	55	0.0	8	0.0	145	NP
242	152	60	0.0	8	0.0	~185	P
240	152	67	0.0	8	0.0	>230	P
81	76	150	65.0	67.8	1.9	~185	P
52	76	200	65.0	67.8	1.9	>185	P
83	76	200	65.0	67.8	1.9	>230	P
82	76	300	65.0	67.8	1.9	230	P
80	76	100	70.0	72.4	2.3	125	P
79	76	150	70.0	72.4	2.3	200	P
49	76	200	70.0	72.4	2.3	230	P
78	76	300	70.0	72.4	2.3	205	P
69	76	200	73.0	75.2	2.7	205	P
50	76	200	75.0	77.1	3.0	160	P
53	195	200	75.0	77.1	3.0	>230	P
70	76	200	77.0	78.8	3.3	100	M
255	150	200	77.2	79.0	3.4	~150	M
51	76	200	80.0	81.5	4.0	75	NP

[a] NP denotes nonpropagation, M denotes marginal propagation, and P denotes propagation.

3.2. Limestone rock dust inerting

For the limestone rock dust inerting tests in the experimental mine, the results were based on tests at the most hazardous fuel dust concentration. In LLEM tests 49 and 78–80, the coal dust loading was varied from 100 to 300 g/m³ while the total inert content of each of the coal and rock dust mixtures remained constant at 72% (Table 3). With the 200-g/m³ coal dust loading (LLEM test 49), the flame traveled about 230 m from the face with a corresponding overpressure (beyond the influence of the methane ignitor) of approximately 0.8 bar (80 kPa). In the 72% total inert tests with 100-, 150-, and 300-g/m³ coal dust loadings, the flame travel and overpressures were lower than for the 200-g/m³ test. Similar data were obtained in the LLEM tests 81–83, where the coal dust loading was varied from 150 to 300 g/m³ and the total inert content was held constant at 68%. With the 200-g/m³ coal concentration (LLEM test 83), the flame traveled greater than 230 m from the face with an overpressure of about 1 bar (100 kPa). With the 150- and 300-g/m³ tests at 68% inert, the flame travel and overpressures were less than for the 200-g/m³ test. In each of these series of tests, the 200-g/m³ coal concentration provided the strongest explosion. The LLEM rock dust inerting tests with the gilsonite dust (at 85% total inert) showed that a concentration of 150 g/m³ produced the longest flame travel and largest pressures. Therefore, the determination of the final amount of limestone rock dust necessary to inert the two fuel dusts was based on LLEM tests at a dust loading concentration of 200 g/m³ for the Pittsburgh pulverized coal and 150 g/m³ for the pulverized gilsonite, since these concentrations produced the most violent explosions. Assuming ideal uniform dispersion of the dust in the LLEM, maximum intensity would be expected to occur just above the stoichiometric concentrations of 210 g/m³ for Pittsburgh coal and 90 g/m³ for gilsonite. These stoichiometric values assume that mainly the volatiles are burning and that the volatility of the coal is ~50% under the high heating rates in flames (see following section on "Explosion Limit Models").

The rock dust inerting tests with pulverized gilsonite and Pittsburgh coal dusts were conducted using test zones 76-, 94-, 150-, and 195-m long (Table 3). For the Pittsburgh pulverized coal dust loading of 200 g/m^3, a coal and limestone rock dust mixture of 79% total inert content (LLEM tests 70 and 255) produced a marginal propagation for both the shorter and longer test zones in the single entry at the Lake Lynn mine. In LLEM test 70, the flame extended somewhat beyond the end of the test zone but at a significantly lower speed and much lower pressure value compared to a typical propagating explosion. In LLEM test 255, the flame radiation was very weak as the flame approached the end of the dusted zone. An 81.5% total inert content mixture (LLEM test 51) extinguished the flame within the dusted zone and resulted in a nonpropagation. Therefore, the rock dust content necessary to prevent an explosion of the Pittsburgh coal in the single entry of the LLEM was 78–80%, and the corresponding total inert content (including the moisture and ash in the coal) was about 80–82%.

The gilsonite dust at loadings of 100 g/m^3 (LLEM test 217) and 150 g/m^3 (LLEM test 226) did not propagate past the test zone when mixed with rock dust to give a total inert content of 90%. However, these same gilsonite loadings propagated over twice the length of the test zone at 85% total inert content or lower. Therefore, the rock dust content necessary to inert the gilsonite in the LLEM is about 88–90%, and the total inert content is also 88–90%.

The amount of limestone rock dust necessary to inert the Pittsburgh coal dust and gilsonite dust was also measured in the 20-L chamber, using 5000-J ignitors (Cashdollar et al., 1989; Cashdollar, 1996; Cashdollar & Hertzberg, 1989). For these tests, regular limestone rock dust was used instead of the fluidized rock dust used for some previous laboratory tests (Cashdollar et al., 1987, 1992; Greninger et al., 1990). The tests were conducted over a wide range of concentrations to determine the worst case. For the Pittsburgh coal, the rock dust content necessary to inert the mixture was about 74%, and the corresponding total inert content was about 76%. For the gilsonite dust, the rock dust content needed to inert the mixture was 90%, and the corresponding total inert content was also 90%. The repeatability of the laboratory data was about ±2% rock dust. These laboratory data show reasonably good agreement with the full-scale experimental mine data.

A summary of the experimental mine and 20-L laboratory limestone rock dust inerting data for various fuel dusts is shown in Fig. 5. The vertical axis shows the amount of rock dust in the mixture necessary to inert the various fuel dusts. The horizontal axis is the moisture–

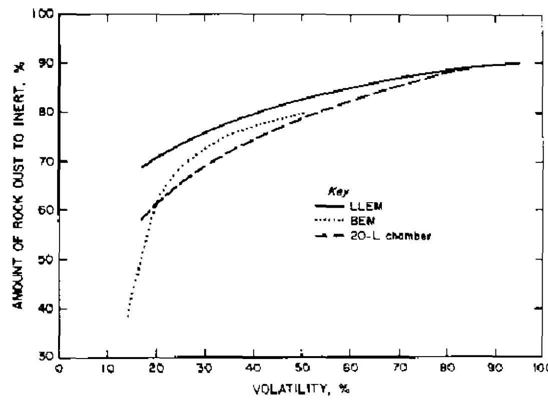

Fig. 5. Rock dust inerting requirements for dusts of different volatilities, showing comparison among Lake Lynn experimental mine (LLEM) data, Bruceton experimental mine (BEM) data, and 20-L laboratory data.

ash-free volatility of the fuel dusts. The dotted curve is a summary of earlier inerting tests in the Bruceton experimental mine (BEM) using a strong ignition source (Nagy, 1981; Richmond, Liebman & Miller, 1975); it corresponds to the amount of rock dust necessary to inert various coals. The Lake Lynn experimental mine data from this report and Weiss et al. (1989) are shown as the solid curve. The 20-L laboratory data (Cashdollar et al., 1989; Cashdollar, 1996; Cashdollar & Hertzberg, 1989) for the same dusts are represented by the dashed curve. The uncertainties in both the experimental mine and laboratory data are of the order of ±3% inert content. The data show that it takes slightly more rock dust to inert the coal dusts in the larger cross section LLEM as compared to that required in the older BEM. The laboratory data show reasonably good agreement with the mine data; therefore, the 20-L chamber can be used for preliminary testing before full-scale mine testing. The regulations for the mining industry, however, are based on the results of the full-scale mine tests.

In addition to the coal and gilsonite dusts, the PRL studied two other types of dusts from the mining industry that are much more difficult to ignite and propagate a flame — oil shales and sulfide ores (Weiss et al., 1996). For the oil shales, explosions did not occur in either laboratory or experimental mine tests for oil assays less than ~85 L/t (~20 gal/ton). For the sulfide ores, explosions did not occur with sulfur contents less than about 20–25%. Further details on this research are in Weiss et al. (1996).

4. Explosion limit models

Two models were compared with the full-scale and laboratory explosion limit data. The first model is based on a thermal balance between the heat generated during combustion of fuel dust and heat abstracted by incombustible material. It is based on the model proposed by Richmond et al. (1975) and Richmond, Liebman, Bruszak & Miller (1979) to describe the limit explosion propagation conditions in a large gallery or mine. This model is similar to that of Palmer and Tonkin (1968, 1971) who investigated the explosibility of organic industrial dusts and coal dust, when mixed with inorganic inert dusts. Volatilization of the fuel dust is assumed to occur rapidly near the leading edge of the flame. The volatiles evolved rapidly from the coal in the flame front are assumed to be significantly higher than those measured by the ASTM D3175 standard test (ASTM, 1999). In addition to the combustion of the volatiles, there may be some combustion of the remaining "fixed carbon" or char, but this is neglected in the model. The fixed carbon char and the added inert dusts are assumed to behave as heat sinks in limiting the maximum temperature. The limestone rock dust is assumed to decompose entirely in the flame. An equilibrium flame temperature, corresponding to the limit flame temperatures for hydrocarbon–air mixtures, is assumed. Heat losses to the walls in large diameter galleries such as the experimental mine should be negligible and are not included in the model.

The energy balance equation is therefore the heat for the rock dust decomposition plus the heating of rock dust plus the heating of coal char plus the heating of the products equals the available heat:

$$Y_r H_d + [Y_r C_r + (Y_c - X_v) C_c] \Delta T + (\rho C_p) \Delta T = H_v X_v \quad (1)$$

where Y_r is the concentration of rock dust, H_d is the heat of decomposition of the rock dust (426 kcal/kg), C_r is the average over temperature for the specific heat of the rock dust (0.29 kcal/kg°C), Y_c is the concentration of fuel dust, X_v is the concentration of volatiles (≤stoichiometric), C_c is the average specific heat of the char (0.25 kcal/kg°C), ΔT is the temperature change from ambient to flame, ρ is the average density of flame products, C_p is the average specific heat of the flame products, and H_v is the heat of combustion of the volatiles. For this model, ρC_p is taken as 0.35 kcal/m^3°C. H_v is taken as 9000–10,000 kcal/kg for the coal volatiles and as 10,000 kcal/kg for the gilsonite volatiles. These input data are the same as those used by Richmond et al. (1975, 1979) and Richmond, Liebman, Bruszak & Miller (1979) except that they used only H_v=10,000 kcal/kg for the coal rather than a range of values. It is understood that some of the input data for this model are only approximate. This model (Richmond et al., 1975) is assumed to be independent of dust particle size as long as the coal is <34 μm and the rock dust is <14 μm. Additional details on the model are in Richmond et al. (1975, 1979).

The second model is more sophisticated than the first model, but still has some uncertainties in input data. For this model, H_v is taken as 9300 kcal/kg for the coal volatiles, calculated based on the measured heats of combustion (moisture and ash free or maf) of Pittsburgh coal and of coke derived from the coal. H_v is taken as 10,000 kcal/kg for the gilsonite volatiles, based on the measured heat of combustion (maf) for the gilsonite. This second model uses the NASA-Lewis CEA-400 Fortran computer code, which is an updated PC version of the CEC-80 code (Gordon & McBride, 1976), which is described in detail in Conti, Zlochower and Sapko (1991). An earlier version of the model is discussed in Hertzberg, Zlochower and Cashdollar (1988). Adiabatic equilibrium calculations of product gas temperatures, pressures, and compositions were made for the various fuel dust and air mixtures. The calculations give the maximum expected explosion temperatures and pressures for the gas mixtures in the absence of a detonation. This model considers each of the flame products individually. The program computes the equilibrium product composition from the listed reactants and their standard energies of formation by examining all possible product species (consisting of combinations of the reactant atoms) whose temperature dependent thermodynamic properties are listed in an auxiliary table. The thermodynamic properties accessed by the program are taken predominantly from the JANAF thermodynamic data compilation (Chase, Davies, Downey, Frurip, McDonald & Syverud, 1985). The product composition is obtained by minimizing the free energy of the system. Constant pressure calculations were performed at one atmosphere to determine the adiabatic temperatures. Such temperature calculations were used to derive limit flame temperatures and compositions.

For both models, the volatiles evolved rapidly from the coal in the flame front were assumed to be significantly higher than those measured by the ASTM D3175 standard test and listed in Table 1. The Pittsburgh coal volatility was taken as 50%, based on rapid pyrolysis experiments (Cashdollar et al., 1989; Hertzberg, Zlochower & Edwards, 1988), rather than the 36% value listed in Table 1. The gilsonite volatility was taken as 90%, somewhat higher than the 84% value listed in the table. The limit flame temperature for both models was taken as 1300 to 1500 K.

Using the two models, limit coal dust and gilsonite concentrations were calculated and compared with experimental data in Table 4. For the Pittsburgh coal, the calculated minimum concentrations ranged from 72 to 97 g/m^3 for the Richmond–Liebman (Eq. (1)) model and from 81 to 102 g/m^3 for the NASA-Lewis CEA-400 model, compared to the 80 g/m^3 in both laboratory chambers and the 60 g/m^3 value from LLEM. The calculations assume that only the volatiles (~50%) burn. If some of the fixed carbon burns or if the volatiles are higher than 50%, the calculated MEC values would be

Table 4
Calculated and experimental minimum explosible concentration (MEC) of Pittsburgh coal and gilsonite dusts

Dust	Minimum explosible concentration (MEC), g/m³			
	20-L & 1000-L chambers	LLEM	Eq. (1) model calculation	CEA-400 model calculation
Pittsburgh coal	80±10	60±5	72–97	81–102
Gilsonite	35±5	35±5	39–47	36–46

lower. There is some evidence that more of the fixed carbon may participate in the mine explosion due to the thicker flame zone (Conti et al., 1991). For the gilsonite, the calculated minimum concentrations ranged from 39 to 47 g/m^3 for the Richmond–Liebman model and from 36 to 46 g/m^3 for the NASA-Lewis model, which are both in fairly good agreement with the experimental value of 35 g/m^3 in both the laboratory and mine tests. For both models, the lower end of the calculated range of MEC-values agrees better with the experimental values for the coal and the gilsonite. The lower end of the calculated range of MEC-values corresponds to the lower value (1300 K) of the limit flame temperature or ΔT=1000°C.

The models were also used to predict the amounts of limestone rock dust necessary to inert the Pittsburgh coal (PPC) and gilsonite. The calculations were made at near-stoichiometric (for the volatiles) concentrations of 220 g/m^3 for the PPC and 100 g/m^3 for the gilsonite, which would be the "worst case" conditions. The Richmond–Liebman model predicts limit rock dust concentrations of 76–82% and the NASA-Lewis CEA-400 model predicts limit rock dust concentrations of 72–78% to inert the Pittsburgh coal, as shown in Table 5. Experimental rock dust concentrations to inert the PPC ranged from 78 to 80% for the mine tests and ~74% for the 20-L chamber. Experimental rock dust concentrations to inert gilsonite ranged from 88% to 90% for the mine and ~90% for the 20-L chamber, compared to 86–88% for the Richmond–Liebman model and 84–88% for the NASA-Lewis model. For both models, the ranges of calculated values overlapped the ranges of experimental values for the coal and the gilsonite. If the models were modified so that not all of the rock dust decomposed, the values calculated by the models would be higher.

Table 5
Limestone rock dust required to inert Pittsburgh coal and gilsonite

Dust	Rock dust to inert, %			
	20-L chamber	LLEM	Eq. (1) model calculation	CEA-400 model calculation
Pittsburgh coal	74±2	78–80	76–82	72–78
Gilsonite	90±2	88–90	86–88	84–88

The agreement is rather good between model predictions and experiments for both the minimum concentrations (lower flammable limits) and for the rock dust inerting concentrations, especially when considering the uncertainties in the model assumptions and in the experimental data, including variations in dispersion methods. Additional experimental research on coal dust and coal–rock dust mixtures, including flame temperature measurements and gas sampling, is needed to better refine these models. Important issues that remain include the estimation of the best value for the volatility of the coal under flame conditions, the extent of char (fixed carbon) burning, and the extent of limestone rock dust decomposition in mine explosions.

5. Explosion dynamics

As described by Nagy (1981), a gas and/or dust explosion in a mine passageway develops two types of destructive pressures — *static* and *dynamic*. The hot combustion products expand and exert a force equally in all directions. This is the static pressure, which is the pressure measured in a closed volume. In a mine, the hot gases also expand and flow through the mine roadways or passageways, pushing air ahead. This flow of gas at high speed generates a wind or dynamic pressure, which is directional. Both the static and dynamic pressures can cause damage during a mine explosion. The static pressure rise can destroy stoppings in side entries perpendicular to the direction of gas flow. The dynamic pressure gives rise to wind forces that can disperse coal dust and that can move objects. The speed and duration of the moving air in a mine explosion entrains dust from the mine surfaces forming a combustible cloud which when ignited causes the most damage in the underground workings. The dynamic pressure is proportional to the square of the air speed as shown by the following equation (Nagy, 1981; Kuchta, 1985): $P=0.5\rho v^2$, where ρ is the air density and v is the air speed.

The maximum static pressure for a coal–air explosion in a laboratory chamber is about 7 bar (700 kPa). In an open mine entry the maximum static pressure is generally less than that due to the pressure release from the gas flow in the mine entry. However, maximum pressures in a mine may exceed 7 bar with pressure piling or a detonation. In pressure piling, the fuel–air mixture ahead of the flame front is compressed. The flame then burns through this compressed mixture with a correspondingly increased maximum explosion pressure (increased by the compression ratio). The next volume of unburned mixture is then compressed additionally to produce an even greater explosion pressure, etc. For example, Cybulski (1975) discusses a coal dust explosion experiment (#1397) in a dead end entry where the peak pressure was at least 4.1 bar (4.1 MPa), causing considerable damage to the Polish Experimental Mine Barbara. Dust explosions in open entries in the Bruceton experimental mine have developed pressures exceeding 10 bar (1.0 MPa) (Nagy, 1981). Pressure piling can, in some cases, lead to a detonation, where shock waves develop at the flame front and the propagation is supersonic relative to the unburned reactants. The maximum explosion pressure of a detonation may be double that of a deflagration (Kuchta, 1985).

A schematic (Hertzberg & Cashdollar, 1987) of a dust explosion in a mine entry is shown in Fig. 6. The effect of turbulence is most pronounced and devastating when the flammable volume is partially confined as in a mine passageway, with one end open and with ignition at the closed end. Hot burned gases generated behind the flame front expand toward the open end and push the unburned mixture outward. The Reynolds number of the unburned mixture flow in the tube or corridor rapidly exceeds the critical threshold for the generation of turbulence. The flame speed then increases as the flame propagates into that turbulent mixture. This acceleration of the flame further increases the turbulence, which further accelerates the flame. This process is idealized in Fig. 6B, where the combustion wave is characterized (Hertzberg & Cashdollar, 1987) as an accelerating piston exerting a pressure force on the unburned gas in the tube, accelerating it toward the open end. The flow disturbance associated with the piston-like motion is transmitted to the gas ahead of it at the velocity of sound, C_o, in the medium. Thus, only a finite volume of gas ahead of the piston is compressed by its motion. The region of gas ahead of the disturbance front cannot sense

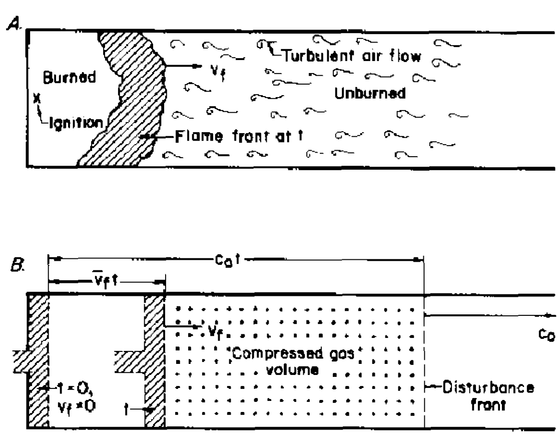

Fig. 6. Propagation of a dust flame from the closed end of a tunnel (A) and idealization of that process as an accelerating piston (B).

the motion of the piston. Only the gas volume in the space between the piston and the leading edge of the sonic disturbance is compressed in the time t, and that volume is A_oC_ot, where A_o is the cross sectional area of the mine passageway and t is the time during which the piston has moved. If ρ_o is the initial cold gas density, during the time t, the mass of gas accelerated by the piston is given by: $m=\rho_oA_oC_ot$. That mass of gas, which was initially at rest, is accelerated to the piston velocity, v_f. From Newton's law, the product of that mass and its instantaneous change in velocity, Δv, must equal the impulse, which is the product of the pressure force, F, and the time over which it is applied (Hertzberg & Cashdollar, 1987; Richmond & Liebman, 1975). Thus:

$$m\Delta v=F\Delta t=\Delta PA_ot \quad (2)$$

$$\rho_oA_oC_ot(v_f-0)=\Delta PA_ot \quad (3)$$

which gives:

$$\Delta P=\rho_oC_ov_f \quad (4)$$

where v_f is the flame speed (or piston velocity) and ΔP is the explosion overpressure at the leading edge of the flame. Hence, the pressure generated by the explosion is linearly proportional to the flame speed, with the speed of sound, C_o as the constant of proportionality. The equation relating these parameters is called the acoustic approximation (Richmond & Liebman, 1975). The general validity of this equation and its more exact refinements has been demonstrated in many gas and dust explosion tests at the Bureau of Mines Bruceton experimental mine (Richmond & Liebman, 1975).

The acoustic approximation (Eq. (4)) shows that the higher the flame speed driving an explosion in a tunnel or mine entry, the higher is the explosion pressure. The faster the flame speed is, the smaller is the compressed gas volume ahead of the wave and the more difficult it is for the compression force to be relieved by the gas motion, resulting in a higher pressure generated by the propagating flame front. When the combustion wave accelerates to reach the velocity of sound in the unburned mixture (or exceeds it), there can be no gas motion ahead of the combustion wave. Thus there can be no release or venting of the pressure. Under these conditions, the combustion process can transit from a deflagration to a detonation.

5.1. Explosion tests to evaluate the strength of underground mine seals

This section discusses some of the flame propagation characteristics as they relate to full-scale testing of the explosion resistance of seals used in underground coal mines. Federal regulations require that abandoned areas of underground mines must be either ventilated or isolated from active workings through the use of seals capable of withstanding the destructive forces from an explosion. In recent years the Lake Lynn experimental mine has been used extensively to evaluate the performance of new seal designs for use in US coal mines (Greninger, Weiss, Luzik & Stephan, 1991; Weiss, Greninger, Stephan & Lipscomb, 1993; Weiss, Cashdollar, Mutton, Kohli & Slivensky, 1999). As described in the "Experimental Facilities and Test Procedures" section, the seals are constructed in the crosscuts between B- and C-drifts (Fig. 3). The explosion resistance characteristics of the seals are evaluated by using gas and dust explosions conducted in the LLEM C-drift. For an explosion giving a static pressure of ~1.4 bar (~140 kPa) against the seals, a 190-m^3 zone of 9% CH_4-air was ignited at the face. For a stronger explosion, 80 kg of coal dust was loaded onto shelves that were suspended from the mine roof on 3-m increments for 64 m beyond the ignition zone (Weiss et al., 1999). This coal dust loading provided a nominal concentration of 100 g/m^3, assuming the dust was uniformly dispersed over the entry cross section. To produce an even stronger explosion, a third test was run with 160 kg of coal dust or a nominal concentration of 200 g/m^3. The results of the seal evaluations are in the references (Greninger et al., 1991; Weiss et al., 1993, 1999) and will not be discussed here. However, various aspects of the explosions used to evaluate the seals will be considered in relation to explosion propagation.

Fig. 7 shows the flame displacement as a function of time for LLEM test 348, which was the gas and 100-g/m^3 coal dust explosion (Weiss et al., 1999). For convenience, the flame travel is divided into four zones. In zone 1, the gas zone is ignited at the face (closed end) of the mine entry, and the flame expands hemispherically at a nearly constant rate until it contacts the walls and roof of the mine entry. It then starts to move outward in the mine entry. The average flame speed in zone 1 was about 15 m/s. In zone 2 (4–26 m from the face), the flame moves linearly down the mine entry at an average flame speed of 83 m/s. The water barrels (Fig. 3) located in the first third of zone 2 serve as obstacles to generate turbulence and increase the flame speed. The effect of the induced turbulence is evident in zone 3, where the average flame speed was 340 m/s. In zone 4 (56–93 m) the flame propagation averages 440 m/s, primarily due to the rapid consumption of dispersed coal dust that was pushed ahead by the expanding combustion products. Flame propagation occurred beyond the 93 m station but was not included in the flame speed calculation because the flame slowed down due to venting into B-drift through failed seals and open crosscuts.

A summary of the flame propagation data for LLEM tests 347, 348, and 349 is listed in Table 6. LLEM test 347 was the gas ignitor zone only. Test 348 for the gas zone and added 100 g/m^3 of coal was described in the previous paragraph. Test 349 was for the gas zone and 200 g/m^3 of added coal. The measured flame speeds through zones 1 to 3 were similar for all three tests. The closed end ignition of the 14-m-long gas zone (~210-m^3 volume) resulted in flame propagation for just beyond 56 m. The influence of added coal dust to the combustion process is indicated by the much higher flame speeds as the explosion propagates through zone 4. The 200-g/m^3 nominal coal dust loading produced an average flame speed about 1.7 times faster than that for the 100-g/m^3 loading. The consequence of this increase in flame speed is best illustrated by the significant increase in resulting explosion pressures.

Fig. 8 shows the static pressures as a function of distance from the face for the three LLEM explosions. Additional details of these tests, including tables of peak pressure versus distance and times of peak pressure are in Weiss et al. (1999). The flame essentially acts as a piston to drive the flow ahead of it. The maximum static pressures within the flow, as well as the maximum gas speeds, occur near the flame front in agreement with the theory of one-dimensional combustion dynamics. LLEM test 347 shows the peak pressures at each station as a

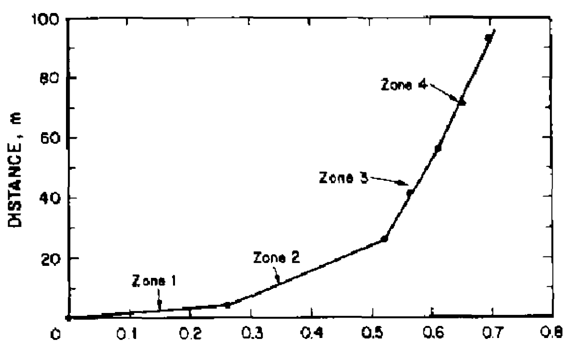

Fig. 7. Flame displacement versus time for LLEM test 348 (methane gas plus 100 g/m^3 coal) propagating in C-Drift.

Table 6
Gas and dust flame speeds from explosions propagating in LLEM C-drift[a]

Flame		Flame speed, m/s		
Zone	Distance, m	LLEM test 347 Gas only	LLEM test 348 Gas+100 g/m^3 PPC	LLEM test 349 Gas+200 g/m^3 PPC
1	0 – 4	14	15	13
2	4 – 26	103	83	100
3	26 – 56	390	340	335
4	56 – 93	—	440	740

[a] Gas ignition zone was 14-m-long or ~210-m^3 of 9% CH_4 in air. Average flame speeds were measured over indicated zones downstream from the point of ignition.

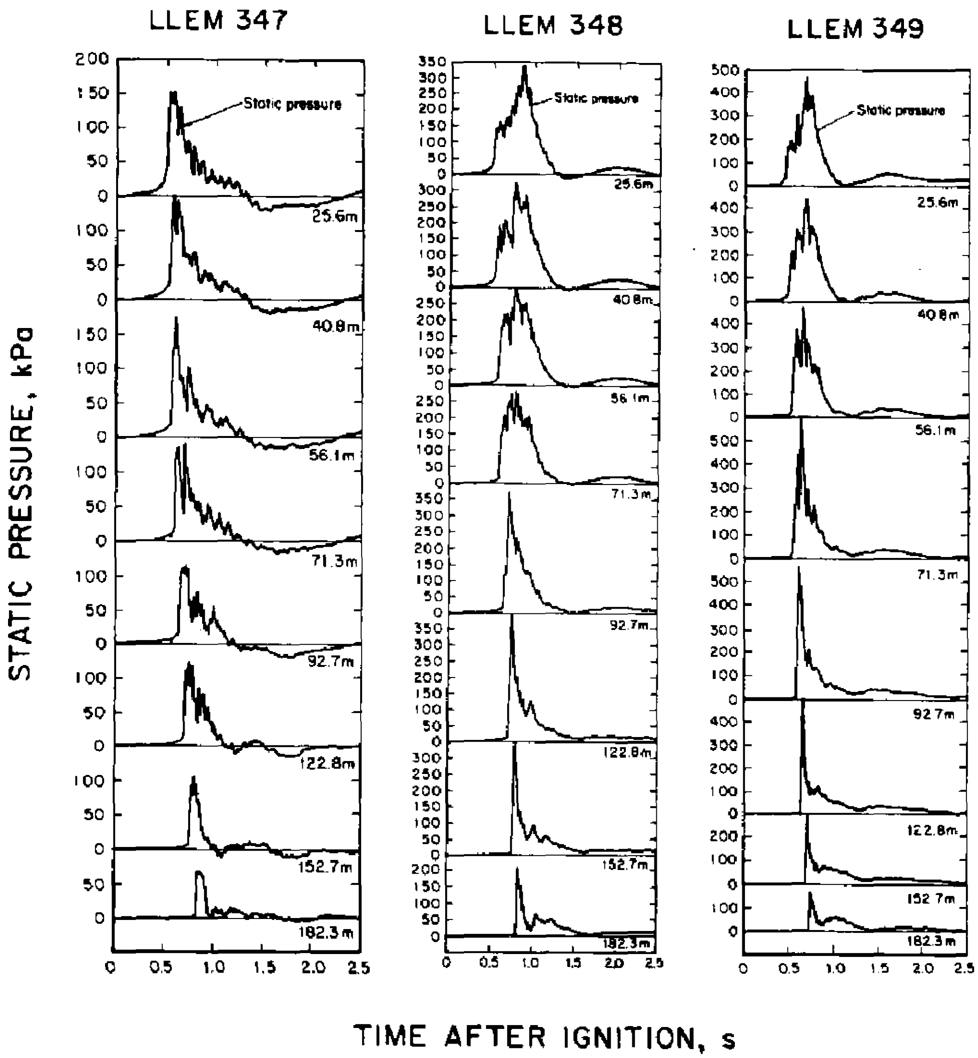

Fig. 8. Pressure wave diagrams for three explosions: LLEM test 347 (CH_4 gas zone only), LLEM test 348 (gas plus 100 g/m^3 coal), LLEM test 349 (gas plus 200 g/m^3 coal).

wave or piston traveling outward from the face. Both the 100- and 200-g/m^3 explosions show strong compression waves being driven in both directions by the accelerating flame. These strong compression waves originate near the 93-m station, in zone 4 where the flame speed is a maximum. The compression wave then travels both inward and outward from the 93 m station. The compression wave travels faster towards the face than away from the face due to the presence of hot gases behind the flame front. The pressure history from the gas zone (LLEM test 347) produces maximum overpressures of about 1.5–1.7 bar (150–170 kPa) at the 26- to 56-m stations and decays to about 0.6 bar (60 kPa) at the 182-m station. Upon closer inspection of the 26-m station pressure histories for the LLEM test 348 and test 349 explosions, one can identify that portion (initial peak at ~1.5 bar) associated with the gas zone combustion prior to the later, higher peak due to the reflected compression wave from the dust combustion. The maximum pressures for the three tests were ~1.7 bar for LLEM test 347, ~3.9 bar for LLEM test 348, and ~6.0 bar for LLEM test 349. The increase in maximum pressure from the 100-g/m^3 coal dust explosion (LLEM test 348) to the 200-g/m^3 coal dust explosion (LLEM test 349) is consistent with the increase in flame speed in zone 4 for the latter explosion (Table 6).

6. Conclusions

The minimum nominal dust loadings for explosion propagation in the Lake Lynn experimental mine were 35 g/m^3 for the 84% volatility gilsonite dust and 60 g/m^3 for the 36% volatility Pittsburgh bituminous coal dust. These data are based on mine experiments using a test zone that was more than twice as long as the flame travel from the ignitor; this avoids the problem of "overdriving" that was found for shorter test zones. In the limestone rock dust inerting tests in the LLEM, the Pittsburgh coal required about 78–80% rock dust or 80–82% total inert content in the coal–rock mixture in order to prevent explosion propagation. The higher volatility gilsonite required about 10% more rock dust than the coal to be inerted. Two theoretical models based on a calculated, adiabatic limit flame temperature were shown to be consistent with experimental mine and laboratory data for both minimum concentrations and the amounts of rock dust necessary to inert the coal and gilsonite. These results for the coal and gilsonite dusts extend the data base for carbonaceous fuels to include a wide range of volatilities. Explosion intensities increased significantly with increasing coal dust concentrations in both small and large scale explosions.

Basic and applied research on dust explosions continues in NIOSH. The basic research, including laboratory experiments and theoretical studies, focuses on improving mine safety through increased knowledge and understanding of complicated dust combustion phenomena. Applied research, mostly conducted in the LLEM, plays a key role in providing the technical data needed to resolve regulatory issues dealing with explosion prevention, detection, suppression, and the performance evaluation of new technologies under realistic large-scale conditions.

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