

Coal dust explosibility

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This paper reports US Bureau of Mines (USBM) research on the explosibility of coal dusts. The purpose of this work is to improve safety in mining and other industries that process or use coal. Most of the tests were conducted in the USBM 20 litre laboratory explosibility chamber. The laboratory data show relatively good agreement with those from full-scale experimental mine tests. The parameters measured included minimum explosible concentrations, maximum explosion pressures, maximum rates of pressure rise, minimum oxygen concentrations, and amounts of limestone rock dust required to inert the coals. The effects of coal volatility and particle size were evaluated, and particle size was determined to be at least as important as volatility in determining the explosion hazard. For all coals tested, the finest sizes were the most hazardous. The coal dust explosibility data are compared to those of other hydrocarbons, such as polyethylene dust and methane gas, in an attempt to understand better the basics of coal combustion.

Keywords: explosion; coal; dust

In mining and other industries that use or process coals, an accurate knowledge of the explosion hazards is essential. Various books such as references 1-7 have been published since 1980 on the general subject of the explosion hazards of dusts and powders. A major source of information on coal dust explosion hazards is reference 8. The present paper concentrates on the subject of the explosion hazards of coal dusts, but the concepts are applicable to many other dusts, and especially to other carbonaceous dusts. The data on coal are compared to those for polyethylene dust, a simple hydrocarbon that is completely volatile, and to methane gas data.

This paper reports US Bureau of Mines (USBM) research on coal dust explosibility. The laboratory data were obtained in the USBM 20 litre chamber⁹ which has been used extensively to study the explosibility of coals and other carbonaceous dusts. Previous USBM papers have discussed various aspects of coal dust explosibility. These included the ignition energy requirements for accurate measurements of flammability limits of dusts and gases^{10,11}, a volatility model for coal dust flame propagation¹², the effect of volatility on the explosibility limits of coals and other carbonaceous dusts¹²⁻¹⁵, the effects of particle size^{16,17}, comparisons of data from 20 litre and 1 m³ chambers^{11,17}, and comparisons of laboratory and experimental mine data^{15,17-19}.

Experimental equipment and test procedures

The dust explosibility experiments in this paper were conducted in the USBM 20 litre laboratory chamber⁹ shown in *Figures 1* and *2*. This is the standard laboratory

test chamber used at the USBM for studying the explosibility and inerting of combustible dusts. There is another style of 20 litre chamber designed by Siwek^{1,5,20,21} that is in wide use in Europe and elsewhere. The USBM 20 litre chamber is near-spherical in shape and made of stainless steel. It has a pressure rating of 21 bar (g). The chamber top is hinged and opens across the full chamber diameter (*Figure 1*), allowing easy access to the interior for positioning instruments and for cleaning. The hinged top is attached with six bolts which are not shown on the drawings. Two optical dust probes²²⁻²⁴ are used to measure the uniformity of the dust dispersion at the positions shown in *Figures 1* and *2*. The optical probes measure the transmission through the dust cloud. Thin jets of air keep the windows of the probe dust-free. References 9 and 18 contain examples of dust probe transmission measurements showing the dispersion uniformity in the 20 litre chamber. The strain gauge pressure transducer measures the explosion pressure and rate of pressure rise (dP/dt). Since it is an absolute pressure gauge, it can also be used during the partial evacuation of the chamber prior to dispersion and for adding gases to the chamber by partial pressures. For very fast explosions, a piezoelectric pressure transducer is also used to measure dP/dt . Multichannel infra-red (IR) pyrometers²⁵⁻²⁷ can be used to measure the explosion temperatures by observing the flame radiation through the sapphire window. A 25 μm (1-mil) Type K (nickel-chromium versus nickel-aluminium) thermocouple was used to measure changes in chamber temperature during dispersion of the dust and air. A 25 μm (1-mil) Type S (platinum versus platinum-rhodium) thermocouple can be used to meas-

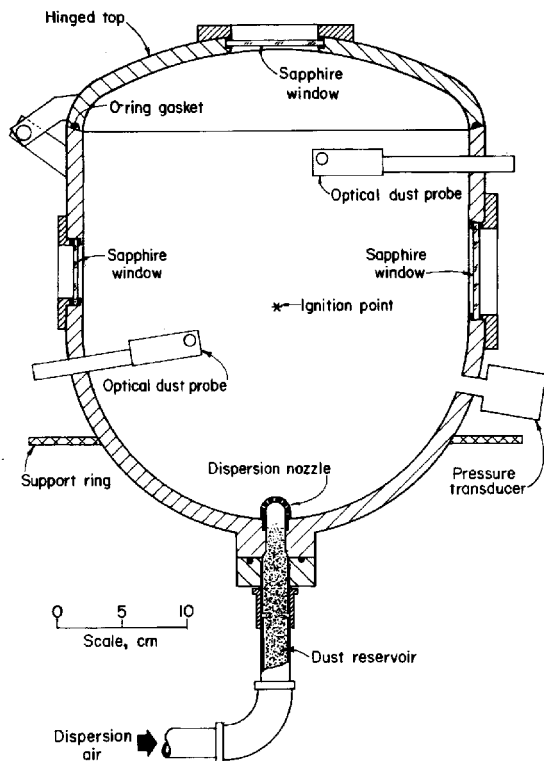


Figure 1 Vertical cross-section of 20 litre explosibility test chamber

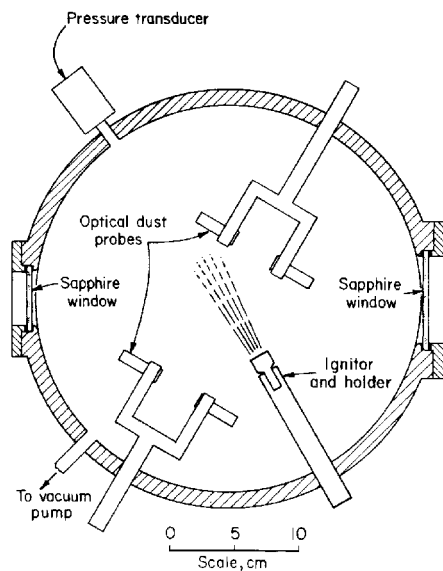


Figure 2 Horizontal cross-section of 20 litre explosibility test chamber

ure the explosion temperature and compare to the IR pyrometer temperature data, similar to tests in a previous 8 litre chamber^{27,28}. A 320 μm (12.5-mil) Type K thermocouple was used to measure the chamber set temperature during tests at an elevated temperature. The data

from the various instruments are collected by a high-speed personal computer (PC)-based data acquisition system. It can sample data from 16 channels at a maximum rate of 9 kHz if all channels are used or at even faster rates if fewer channels are used. Pressure, dP/dt , transmission, and calculated temperature data can be displayed on a colour monitor immediately after each test. The USBM-designed software program allows for variable smoothing, rescaling, peak searches, expansion of the time scale, etc.

The dust to be tested can be placed either in the dust reservoir or on top of the dispersion nozzle at the bottom of the chamber (*Figure 1*). The reported experimental dust concentration for the 20 litre chamber is the mass of dust divided by the chamber volume. After the dust and ignitor (*Figure 2*) have been placed in the chamber, the top lid is bolted on and the chamber is partially evacuated to an absolute pressure of 0.14 bar (a). Then a short blast of dry air (0.3 s duration at 9 bar (g) from a 16 litre reserve tank) disperses the dust and raises the chamber pressure to about 1 bar (a). The ignitor is activated after an additional delay of 0.1 s. This results in a total ignition delay of 0.4 s from the start of dispersion until ignition for the standard test procedure in the USBM 20 litre chamber. The standard procedure for the Siwek 20 litre chamber has a total ignition delay of ~ 0.1 s and a reservoir pressure of 20 bar, resulting in a higher level of turbulence.

The ignition sources used for the 20 litre tests were electrically activated pyrotechnic ignitors manufactured by Fr. Sobbe of Germany. These ignitors are composed of 40% zirconium, 30% barium nitrate, and 30% barium peroxide. They are activated electrically with an internal fuse wire and deliver their energy in about 10 ms. When ignited, they produce a dense cloud of very hot particles and little gas¹⁰. The Sobbe ignitors are available in various energies from 250 to 10 000 J. For the 20 litre tests reported in this paper, 2500 and 5000 J ignitors were used. These energies are nominal calorimetric values based on the mass of pyrotechnic powder in each ignitor. The 2500 and 5000 J ignitors by themselves produce pressure rises of about 0.28 and 0.55 bar, respectively, in the 20 litre chamber. The 2500 J ignitor is comparable in energy to an entire book of 20 pocket matches, all ignited at once.

Examples of the pressure data for a weak and a moderate coal dust explosion are shown in *Figures 3* and *4*. In both figures, the absolute pressure (A) and rate of pressure rise (B) are plotted versus time. *Figure 3* shows the data for a 20 litre chamber explosion test of a low volatile bituminous coal at a dust concentration of 125 g m^{-3} , which is just above the minimum required for

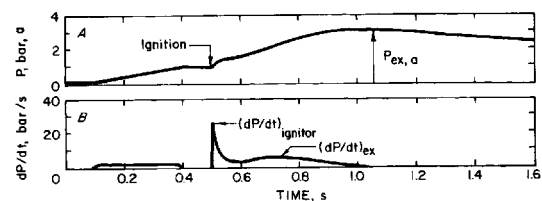


Figure 3 Typical data for a weak explosion of low-volatile bituminous coal at 125 g m^{-3} in the 20 litre chamber

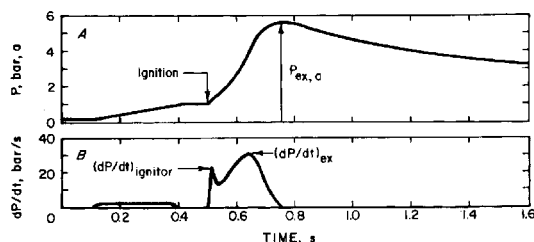


Figure 4 Typical data for an explosion of low-volatile bituminous coal at 200 g m^{-3} in the 20 litre chamber

an explosion. The pressure trace in *Figure 3A* starts at the partially evacuated value of 0.14 bar (a). The blast of air that disperses the dust starts at 0.1 s and ends at 0.4 s on the pressure–time trace. The ignitor is activated at 0.5 s at a chamber pressure of 1.0 bar (a). The maximum explosion pressure is about 3 bar (a). In *Figure 3B*, the rate of pressure rise, $(dP/dt)_{\text{ignitor}}$, for the ignitor is larger than $(dP/dt)_{\text{ex}}$ for the dust explosion itself. The USBM software program allows the user to move the peak search starting point beyond the effects of the ignitor and then determine $(dP/dt)_{\text{ex}}$. *Figure 4* shows data for a larger explosion of the low-volatile coal dust at a higher concentration of 200 g m^{-3} . The maximum explosion pressure is about 5.5 bar (a). For the research in this paper, the criteria for significant flame propagation in the 20 litre chamber were the same as used previously at the USBM^{10,11,17}. These criteria are that the maximum explosion pressure, $P_{\text{ex}} \geq 2 \text{ bar}$ (a) and that the volume normalized rate of pressure rise, $(dP/dt)V^{1/3} \geq 1.5 \text{ bar m s}^{-1}$.

Previously, when the pressure trace for the dust and air dispersion had been viewed on an expanded scale, a slight drop-off in pressure after the end of the dispersion had been observed. Recently, a separate series of dispersion tests (no ignitor) were run at ambient and elevated initial chamber temperature to study this effect. The $25 \mu\text{m}$ fast response Type K thermocouple (TC) was positioned near the center of the 20 litre chamber during these tests to monitor rapid changes in gas temperature. In air dispersion tests where the 20 litre chamber was initially at ambient temperature ($\sim 22^\circ\text{C}$), the TC temperature increased during the dispersion process and was $\sim 70^\circ\text{C}$ at the time the ignitor would normally be activated, decreasing to $\sim 55^\circ\text{C}$ after an additional 1 s, and eventually back to ambient. When air and 400 g m^{-3} of coal dust were dispersed, the TC temperature at the normal ignition time was $\sim 60^\circ\text{C}$, decreasing to $\sim 50^\circ\text{C}$ after 1 s. This measured temperature increase during dispersion and later drop-off explains the observed drop-off in pressure. The gas has been heated in some manner during the dispersion procedure and later cools back to ambient temperature. This cooling causes the drop-off in pressure after the end of the dispersion pulse. This pressure drop-off effect has also been noted by Mintz²⁹ and Lightfoot³⁰. However, their thermocouples were larger, and they were not able to completely follow the rapid temperature changes. The significance of this $\sim 60^\circ\text{C}$ temperature at ignition on the measured data will be discussed later in the paper.

The USBM has historically placed more emphasis on the measurement of minimum explosible concentrations

(MEC) and rock dust inerting amounts rather than on the measurement of rates of pressure rise (which are used for vent sizing) because it is not possible to vent mine explosions. This is the main reason that the dispersion time is longer and the turbulence level is lower for the standard dispersion procedure in the USBM 20 litre chamber than for the Siwek 20 litre chamber. This should mainly affect the rates of pressure rise (at high concentrations) and should not affect MEC measurements¹¹. An advantage of the lower turbulence for the USBM standard dispersion procedure is that the effects of the ignitor are more easily separated from the dust explosion (*Figures 3 and 4*), which is useful for MEC testing. The rate of pressure rise data reported in this paper from the USBM 20 litre chamber should only be used as relative data for comparison of different dusts and should not be used for the sizing of vents according to ASTM Standard E1226, ISO Standard 6184/1, NFPA Guide 68, and VDI Standard 3673, which are based on the higher turbulence level of the Siwek 20 litre chamber and the 1 m^3 chamber^{1,5}.

In this paper, the terms ‘flammability’ and ‘explosibility’ are used interchangeably to refer to the ability of an airborne dust cloud and/or gas mixture to propagate a deflagration after it has been initiated by a sufficiently strong ignition source. Historically, the term ‘flammability’ has been used more for gases and ‘explosibility’ more for dusts.

Experimental data and discussion

The coal that has been used as a standard^{18,31,32} at the USBM since the early 1900s is Pittsburgh seam high-volatile bituminous (hvb) coal. The proximate analyses and heating values of the Pittsburgh coal and a Pocahontas seam low-volatile bituminous (lvb) coal are listed in *Table 1*. The standard Pittsburgh pulverized coal (PPC) dust used for both laboratory and experimental mine testing^{18,31,32} has 80% minus 200 mesh ($< 75 \mu\text{m}$) and a mass median particle diameter of $48 \mu\text{m}$. The mass (volume) and surface weighted particle size distributions for the PPC are shown in *Figure 5*. The size distributions were measured by a combination of sonic sieving and Coulter counter analyses. The PPC has a fairly broad size distribution and is meant to represent the float coal dust carried by the ventilation air in mines³². In order to determine particle size effects on explosibility, various narrow size distributions of Pittsburgh coal were also generated by centrifugal classification and by sieving. Examples of these narrow size distributions are shown in *Figure 6*, where they are compared to the dashed line showing the broader size distribution of the PPC.

Table 1 Proximate analyses and heating values for coals

	Pittsburgh	Pocahontas
Moisture (%)	1	1
Volatility (%)	37	17
Fixed carbon (%)	56	76
Ash (%)	6	6
Heating value (cal g^{-1})	7720	8050

Proximate analyses measured by ASTM D3172. Heating values measured by ASTM D1989.

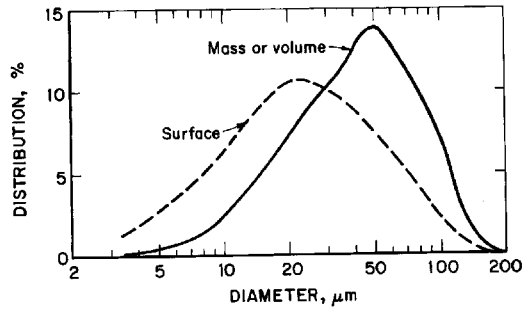


Figure 5 Comparison of surface-weighted and volume-weighted distributions of standard Pittsburgh pulverized coal (PPC)

The majority of data in this paper are for Pittsburgh seam high-volatile coal and for Pocahontas seam low-volatile coal. Size data for various broad size distributions of these two coal dusts are listed in *Tables 2* and *3*. In the tables, the first row identifies the coal by coal seam and number (Pgh-1, etc.) and by additional descriptive notation (date, mesh size, etc.). The size data were measured from a combination of sonic sieving and Coulter counter analyses. The second and third rows list the percentage by weight of each dust less than 20 or 75 μm , respectively. Since particle size distributions generally

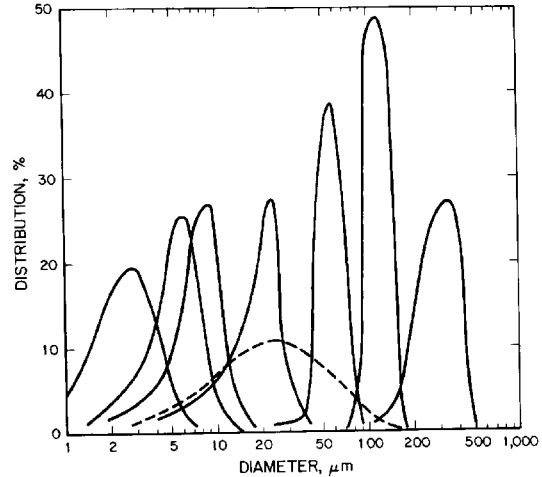


Figure 6 Surface-weighted distributions of several narrow size distributions of Pittsburgh coal, compared to the dashed curve for the broad distribution PPC

approximate a log-normal distribution, the geometric size parameters are listed in rows four and five. The fourth row lists the geometric mass mean particle diameter, \bar{D}_g , and the fifth row lists the dimensionless geo-

Table 2 Size analyses and explosibility data of Pittsburgh high volatile coal

	Pgh-1 -40 M	Pgh-2 -70 M	Pgh-3 PPC	Pgh-4 -200 M	Pgh-5 PPC, fines	Pgh-6 special	Pgh-7 fines
< 20 μm (%)	4	13	13	26	42	42	83
< 75 μm (%)	24	54	80	100	90	94	100
D_g (μm)	132	57	43	29	26	23	11
σ_g	2.5	2.3	1.9	1.8	2.6	2.2	1.8
D_{med} (μm)	163	68	48	32	28	24	11
D_w (μm)	179	76	52	34	37	32	14
D_s (μm)	77	37	34	24	16	17	9
D_s (%T) (μm) @ 100-200 g m^{-3}	35-48	22-27	17-40	16-24	9-10	7-11	5-9
D_s (%T) (μm) @ 300-600 g m^{-3}	48-58	29-42	23-45	27-36	12-19	—	8-15
MEC (g m^{-3})	130	85	80	65	75	~60	85
P_{max} (bar)	6.0	6.3	6.6	6.7	6.8	—	7.1
$(dP/dt)V^{1/3}$ (bar m s^{-1})	19	25	39	41	54	—	59
MOC (%O ₂)	—	—	11	—	—	—	10.5
Amount of rock dust to inert (%)	53	68	74	79	83	83	87

Dashes indicate that no data were available.

Table 3 Size analyses and explosibility data of Pocahontas low volatile coal

	Poc-1 -120M	Poc-2 1/78	Poc-3 3/88-4	Poc-4 6/80	Poc-5 3/88-2,3	Poc-6 2/88-1	Poc-7 fines
< 20 μm (%)	10	27	38	40	46	67	83
< 75 μm (%)	~75	65	75	86	86	94	100
D_g (μm)	~48	39	32	26	24	15	11
σ_g	1.9	3.0	3.2	2.6	2.8	2.4	1.9
D_{med} (μm)	~52	47	30	27	22	14	10
D_w (μm)	~58	63	60	41	40	23	13
D_s (μm)	39	19	18	17	15	11	9
D_s (%T) (μm) @ 100-200 g m^{-3}	17-34	9-14	—	6-10	—	—	—
D_s (%T) (μm) @ 300-600 g m^{-3}	20-40	14-27	—	—	—	—	—
MEC (g m^{-3})	120	130	~100	~90	80	80	~80
P_{max} (bar)	6.0	~6.3	—	6.3	6.2	6.5	6.5
$(dP/dt)V^{1/3}$ (bar m s^{-1})	17	~16	—	~26	—	34	31
Amount of rock dust to inert (%)	60	64	76	78	77	82	83

Dashes indicate that no data were available.

metric standard deviation, σ_g . For a monodisperse size distribution, $\sigma_g = 1.0$. The larger σ_g is, the broader the size distribution. The sixth row lists the mass median particle diameter, D_{med} , which is the 50% point on the cumulative mass distribution. This is perhaps the most commonly reported size characteristic of a dust. The next two rows list the arithmetic mass or volume mean particle diameter, D_w , and the arithmetic surface mean diameter, \bar{D}_s . The next two rows list \bar{D}_s as calculated from the optical dust probe transmission (%T) data as the dust is dispersed in the 20 litre chamber, as described in the next paragraph. One purpose for listing the various size parameters in *Tables 2 and 3* is to show that no one parameter is sufficient to characterize a dust. The explosibility data in the remaining rows will be discussed later in the paper.

The 20 litre chamber test data for the PPC dust (Pgh-3 in *Table 2*) with a 2500 J ignitor are shown in *Figure 7* as a function of dust concentration. These data were collected during many series of tests over a period of six years. At the top of the figure, the transmission data measured by the optical dust probes are shown. As described in reference 23, the transmission T is related to the mass concentration C_m by Bouguer's law:

$$T = \exp(-3QC_m/2\rho\bar{D}_s),$$

where Q is a dimensionless extinction coefficient, l is the path length, ρ is the density of a particle, and \bar{D}_s is the surface mean particle diameter. The data in *Figure*

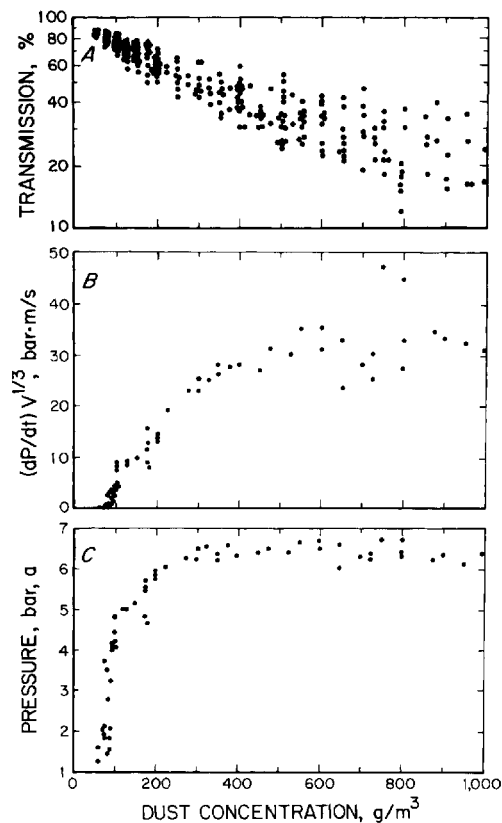


Figure 7 Explosibility data for Pittsburgh (high-volatile bituminous) pulverized coal dust in the 20 litre chamber

7A generally follow the expected linear relationship on this semi-logarithmic plot. At the highest dust concentrations, there is some upward curvature, probably due to increased agglomeration. The scatter in the data is probably due to variations in the agglomerated particle size of the air-dispersed dust. The surface mean particle diameter can be calculated from the measured transmission data (*Figure 7A* and similar graphs), using the above equation. The data are reported as $\bar{D}_s(\%T)$ in *Tables 2 and 3*. In general, \bar{D}_s measured by the particle size analysers is within the range of $\bar{D}_s(\%T)$ measured by the dust probes.

In *Figure 7B*, $(dP/dt)V^{1/3}$ is the volume-normalized maximum rate of pressure rise. Note again that the turbulence level is lower in the USBM 20 litre chamber, and therefore the $(dP/dt)V^{1/3}$ data are not recommended for the sizing of vents. The data are, however, useful as a relative measure of explosion hazard. At the higher turbulence level recommended in ASTM Standard E1226, the maximum $(dP/dt)V^{1/3}$ data for this Pittsburgh coal would be roughly three times higher. The maximum absolute explosion pressures (with the pressure rise of the ignitor subtracted) are shown in *Figure 7C*. Because there are small variations from test to test in the chamber pressure at the time of ignition, these data were normalized to a starting pressure of 1.0 bar (a). The data in *Figure 7* show that, below a certain dust concentration, explosions are not observed. This is the minimum explosible concentration (MEC) or lean flammable limit (LFL). For the PPC, the measured MEC in the 20 litre chamber is $\sim 80 \text{ g m}^{-3}$. This laboratory MEC value is the same as the $\sim 80 \text{ g m}^{-3}$ MEC value^{11,17} measured for the PPC in a 1 m^3 chamber using a 10 kJ ignitor and is comparable to the $\sim 60 \text{ g m}^{-3}$ value^{15,17} measured for the PPC in the USBM Lake Lynn Experimental Mine, using a 152 m long dusted zone and a methane ignition zone. At higher dust concentrations in *Figure 7*, the maximum pressures and rates of pressure rise level off as all of the oxygen in the chamber is consumed, but there is no evidence of a rich limit for the PPC dust.

A summary of the 20 litre chamber pressure versus concentration data for the PPC is shown in *Figure 8*,

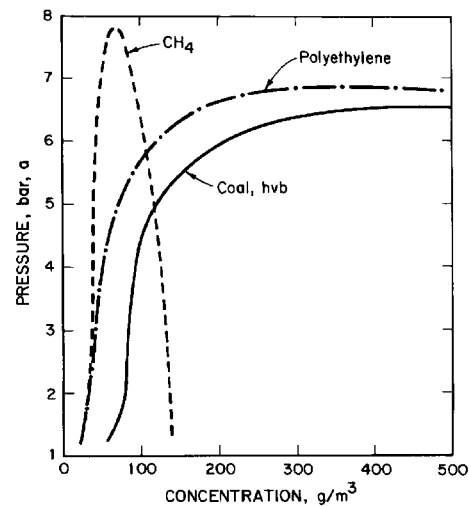


Figure 8 Explosibility of Pittsburgh high-volatile bituminous coal dust, compared to polyethylene dust and methane gas

where the data are compared to those for polyethylene dust and methane (CH_4) gas. Only the average curves are shown and not the data points for individual tests as in *Figure 7*. The CH_4 data are from reference 10, using 500 to 1000 J ignitors because the CH_4 is much easier to ignite than the dusts. The two dusts were tested using 2500 J ignitors. The curve for the polyethylene dust is similar in shape to that for the PPC, except that the polyethylene has a lower MEC and a slightly higher maximum explosion pressure. This is because the polyethylene has a volatility of 100% compared to 37% volatility for the coal, and it has a higher H:C ratio than the coal. The methane gas has a LFL or MEC similar to that of the polyethylene. This shows that the completely volatilizable polyethylene reacts similarly to the methane gas at low concentrations¹². For hydrocarbon gases or dusts, the measured LFL or MEC generally corresponds to a calculated adiabatic temperature¹² of 1300–1500 K. This is the ‘limit flame temperature’, which is the minimum temperature needed to keep a flame propagating. Experimentally, the LFLs of most hydrocarbon gases are easy to measure because the gases have low ignition energies. Much stronger ignition energies are needed for dusts^{10,11}. However, if too strong an ignition energy is used relative to the test chamber volume, the result will be an overdriven ignition¹¹. A standard method for measuring the MEC of a dust cloud is ASTM E1515, which is based on the USBM test procedures described here.

In contrast to the two dusts in *Figure 8*, the methane gas shows a rich limit. For the dusts, the maximum pressures level off at concentrations of 200–300 g m^{-3} as all of the oxygen in the chamber is consumed. At even higher dust concentrations, although the mixtures are nominally fuel-rich, the pressure nevertheless remains constant. The normal rich limit observed for hydrocarbon gases such as CH_4 is not observed for the dusts. An explanation of this effect, at least for many dusts, is that the solid-phase fuel must first devolatilize before it can mix with the air¹². As soon as sufficient volatiles are generated to form a stoichiometric concentration of volatiles in air, the flame front propagates rapidly through the mixture before excess fuel volatiles can be generated.

Figure 9 shows explosibility data for the high-volatile PPC dust and for polyethylene dust at very high concentrations. This shows that these dusts explode even at concentrations beyond 4000 g m^{-3} . There is, of course, an increased uncertainty in the dust dispersion effectiveness at these very high concentrations. The decrease in pressure at higher concentrations may be due to the increased heat sink of the very large dust concentration. The decrease in dP/dt at higher concentrations may be due to the increased heat sink effect and to the possible decrease in turbulence due to the large mass of dust. Deguingand and Galant³³ had previously observed an apparent upper limit at $\sim 4 \text{ kg m}^{-3}$ for coal dust, but this may have been only an ignitability limit because they used an electric spark ignition source that was much weaker than the 2500 J Sobbe ignitor used here. In early large-scale USBM tests (reported by Nagy³²) in the Bruceton Experimental Mine, an upper limit of $\sim 5 \text{ kg m}^{-3}$ was observed for a coarser coal dust. Cybulski⁸ reported an upper limit of $\sim 1 \text{ kg m}^{-3}$ for pulverized coals in tests

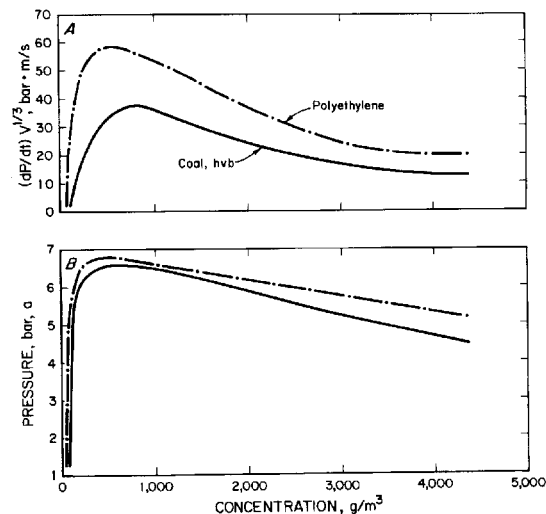


Figure 9 Explosibility data for high-volatile bituminous coal dust, compared to those for polyethylene dust

at the Polish Experimental Mine Barbara. Mintz³⁴ observed some upper limits under conditions of reduced oxygen and at large coal particle sizes. The general conclusion of all of this research is that, for most practical purposes, these dusts have no rich limit of explosibility.

Additional MEC, P_{max} , and $(dP/dt)V^{1/3}$ data for various size distributions of the Pittsburgh and Pocahontas bituminous coals are found in *Tables 2* and *3*. In general, the high-volatile Pittsburgh coals have lower MEC values, higher explosion pressures, and higher $(dP/dt)V^{1/3}$ values than the low-volatile Pocahontas coals of similar size. The effect of volatility on the MEC was also noted by Amyotte and others^{35,36} in a 26 litre chamber. However, the finest sizes of Pocahontas coal in *Table 3* have explosibility data comparable to those of the larger sizes of the Pittsburgh coal in *Table 2*. This shows that particle size is at least as important as volatility in understanding the explosion hazards of coals.

The previous explosibility data were measured using rather broad size distributions of the coals. The USBM has also studied the effect of particle size on the explosibility of dusts by using narrow size distributions, such as those in *Figure 6*. *Figure 10* shows explosibility data from the 20 litre chamber for Pittsburgh coal dust as a function of mass median particle diameter, using 2500 J ignitors. The data for the narrow distributions are shown as solid circles and a solid curve. These data for narrow distributions are compared to the data points (x) for the broad distributions from *Table 2*. The MEC values in the bottom section of the figure are relatively independent of particle size for the finer sizes. At the larger sizes, above 100 μm , the MEC values increase with particle size until a size is reached that cannot be ignited. The top two sections of *Figure 10* show that the maximum pressures and rates of pressure rise are found at the finest sizes tested. The pressures decline slowly and the pressure rise rates decrease faster with increasing particle size. At some size above 200 μm , the narrow sizes of Pittsburgh coal dust can no longer be ignited by the 2500 J ignitor. These data are typical for narrow size distributions of carbonaceous fuel dusts. A broad size distribution is just

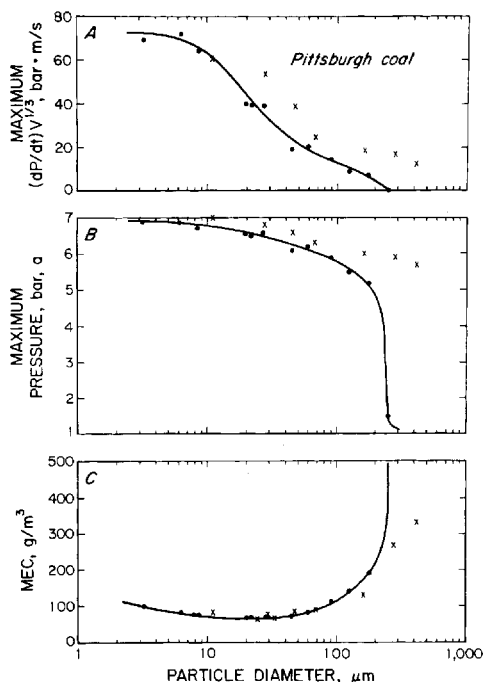


Figure 10 Effect of dust particle size on the explosibility of Pittsburgh coal, \bullet for narrow distributions and \times for broad distributions

a combination of narrow distributions, and these data show that it is the finer particles in a broad distribution that contribute the most to its hazard. The MEC data points for the broad size distributions show little difference from the narrow size distribution data below $D_{\text{med}} \approx 100 \mu\text{m}$. However, the broad size distributions ignite and propagate at larger D_{med} sizes than the narrow size distributions. The pressure and dP/dt data for the broad size distributions are somewhat higher than those for the narrow size distributions, even in the D_{med} range of 20–100 μm . This is probably due to the effects of the tail of fine particles in the broad size distributions. These fine particles were removed from the narrow size distributions. The main conclusion of *Figure 10* is that particle size has an important effect on the explosibility of coal dusts.

A separate series of tests were made to investigate possible changes in particle size during dispersion in the 20 litre chamber. That is, do the coal particles break up during dispersion, resulting in a smaller average size for the tested dust? Minus 200 mesh samples of Pittsburgh and Pocahontas coals were dispersed in the 20 litre chamber. Coulter counter particle-size analyses were made of samples of the original dust and of the dust that had settled to the bottom of the 20 litre chamber after the standard dispersion procedure. For each dust, D_{med} and \bar{D}_w decreased by about 5% and \bar{D}_s decreased by about 10%, relative to the size of the original dust. These decreases are barely significant, considering the uncertainties in sampling and particle-size analysis. Some other dusts may fragment significantly during dispersion. In previous tests with the USBM 20 litre chamber, larger TNT particles fragmented to less than half their original size during dispersion.³⁷ In *Table 2*, when comparing \bar{D}_s from

the particle analysers with $\bar{D}_s(\%T)$ from the dust probes, there is also some evidence that the -40 mesh Pittsburgh coal has fragmented somewhat during dispersion.

Examples of scanning electron microscope (SEM) photomicrographs of coal before and after explosions are shown in *Figure 11*. The dust was a narrow size distribution of Pittsburgh coal with $D_{\text{med}} = 23 \mu\text{m}$. The original unburned particles are shown at two magnifications on the left side of the figure. They are compared to the 'burned' post-explosion particles in the four frames on the right side of the figure. The burned particles are mainly char residues that are often larger than the original particles. In the flame, the bituminous coal particles become molten as shown by the rounded particles on the right. Some particles form cenospheres. The particles also devolatilize in the flame. The volatiles are emitted through the 'blow holes' seen in the char residues. Additional SEM photomicrographs for various post-explosion residue dusts are shown in reference 38.

One of the ways to prevent a dust explosion is to inert the atmosphere so that there is insufficient oxygen for a flame to propagate. One of the most common inerting gases is nitrogen, which is the main constituent of air. To determine the limiting oxygen concentration for coal dust explosions in the 20 litre chamber with 2500 J ignitors, the dusts were dispersed with various oxygen-nitrogen mixtures instead of normal air at 20.9% O_2 . *Figure 12* is an example of the reduced-oxygen data for PPC. The explosions are denoted by the solid circles and the non-explosions by the open circles. The data for PPC in air are shown at the top of the figure at 20.9% O_2 . At the bottom of the figure, explosions still occur at 14% down to 12% O_2 . Based on the data in *Figure 6*, the minimum oxygen concentration (MOC) for propagation of an explosion of this PPC dust is $11 \pm 0.5\% \text{O}_2$. MOC data for two sizes of Pittsburgh coal are listed in *Table 2*. The data show only a slight decrease in the MOC value at the finer size.

The effect of temperature on the ignitability and explosibility of the Pittsburgh coal dust is shown in *Figure 13*. The dotted curve (from reference 39) shows the auto-ignition temperature for the PPC as a function of dust concentration, as measured in the USBM 6.8 litre furnace³⁹. The dotted curve is the temperature boundary between the upper region of the graph where the coal dust cloud will thermally auto-ignite and the lower region where the dust may be flammable but does not thermally auto-ignite. At the higher concentrations in the figure, the thermal ignition boundary levels off to a value of $\sim 530^\circ\text{C}$. This is the minimum auto-ignition temperature (MAIT) for the Pittsburgh coal as measured in the 6.8 litre furnace. This furnace and test method are listed in ASTM standard test E1491.

Explosibility tests were also conducted in the 20 litre chamber at temperatures above ambient but below the temperature at which the dust would auto-ignite. For these tests, the 20 litre chamber was wrapped with electrical heater tape and insulated to reach the elevated temperature. The 320 μm thermocouple measured the set temperature of the 20 litre chamber before the test. The 25 μm thermocouple was used during initial tests to measure the temperature during dispersion of the dust and air. The solid circle data points show MEC data for

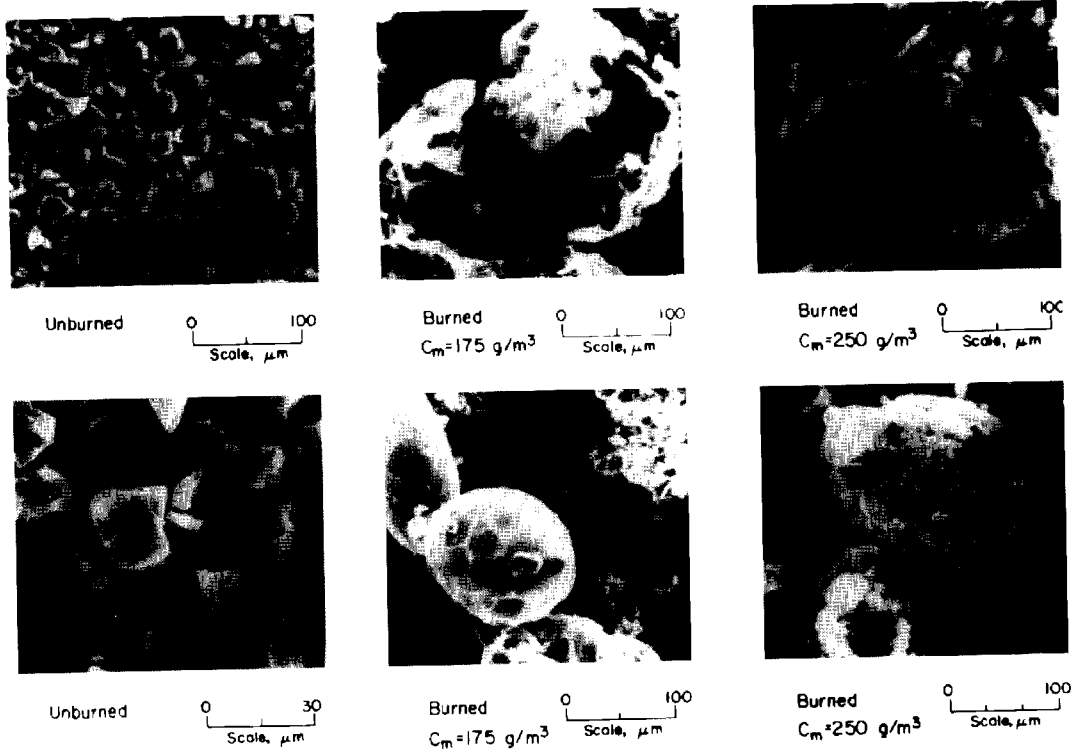


Figure 11 Scanning electron photomicrographs of bituminous coal particles before and after explosions

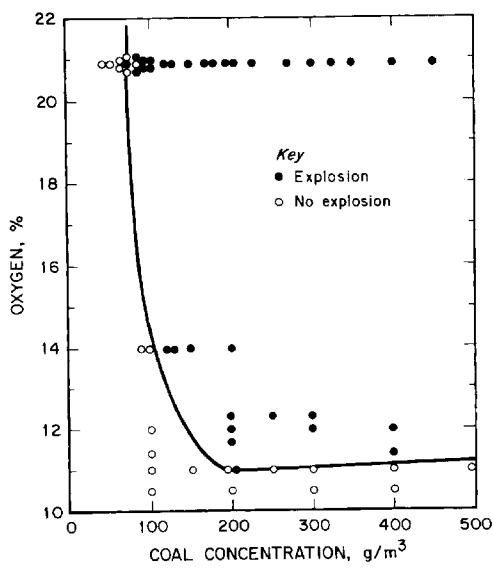


Figure 12 Effect of oxygen concentration on coal dust explosibility

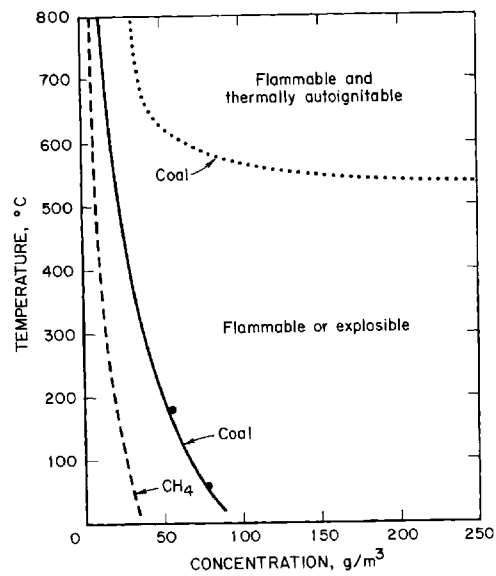


Figure 13 Effect of temperature on the flammability and thermal ignitability of Pittsburgh coal, compared to methane gas

the PPC from the 20 litre chamber at near ambient temperature ($\sim 60^\circ\text{C}$) and at an elevated temperature of $\sim 180^\circ\text{C}$. The experimental data points are extrapolated to even higher temperatures (solid curve) using the modified Burgess-Wheeler law^{40,41} for hydrocarbons:

$$C_T = C_{T_0} \left(\frac{273 + T_0}{273 + T} \right) [1 - 0.000721(T - T_0)],$$

where C_T is the limit in terms of mass concentration at temperature T , C_{T_0} is the limit at T_0 , and the temperatures are in $^\circ\text{C}$. The concentrations to the right of the solid curve are flammable or explosible and the region to the left of the curve is non-flammable. For comparison, the measured lean flammable limit data for methane gas as a function of temperature (dashed curve, from reference 42, p 43) are also shown.

At higher dust concentrations, the maximum explosion pressure for the Pittsburgh coal was also measured at elevated temperature in the 20 litre chamber, using 2500 J ignitors. At near ambient temperature, P_{max} for the PPC was 6.6 bar (a). At an elevated temperature of $\sim 180^{\circ}\text{C}$, P_{max} was 4.8 bar (a). This observation of lower explosion pressures at elevated temperature was also reported previously by Wiemann⁴³. The inverse relationship of explosion pressure with initial temperature is expected from the perfect gas law because there are fewer oxygen molecules at elevated temperature to react with the coal. The ratio of measured maximum explosion pressure (absolute) at $\sim 180^{\circ}\text{C}$ (453 K) to P_{max} at near ambient temperature is the same as the ratio of ambient to elevated temperature in Kelvin. For this comparison, the measured value of $\sim 60^{\circ}\text{C}$ (333 K) has to be used for the tests at near ambient temperature, as discussed in the section on 'Experimental equipment and test procedures'. This analysis shows that the maximum explosion pressure would actually be $\sim 13\%$ higher if the ambient temperature tests were made at $\sim 22^{\circ}\text{C}$ (295 K). This may explain, in part, why the measured maximum explosion pressures in the 1 m^{-3} chamber are $\sim 30\%$ higher than those measured in 20 litre chambers²¹. In the 1-m^{-3} procedure, much less air is injected into the chamber than for the 20 litre procedure. Therefore, the temperature rise during dispersion would be expected to be much less in the 1 m^{-3} chamber, so the tests would be closer to ambient.

The minimum oxygen concentration for the Pittsburgh coal was also measured at elevated temperature in the 20 litre chamber. The measured MOC value for the PPC decreased from $\sim 11\%$ at near ambient temperature to $\sim 10\%$ at $\sim 180^{\circ}\text{C}$. This observation of lower MOC values at elevated temperature was also reported previously by Wiemann⁴³.

The effect of initial chamber pressure¹⁰ on the MEC or LFL is shown in Figure 14. When the methane concentration is expressed in vol% in Figure 14A, the LFL is shown to be constant as the pressure varies from 0.5 to 3 bar. When the CH_4 is expressed in mass concentration in Figure 14B, the LFL is shown to vary linearly with pressure. In Figure 14C, the LFLs of the Pittsburgh coal and polyethylene dusts also vary linearly with pressure.

Another important factor in the explosibility hazard of a dust is the possible co-presence of a flammable gas. Hybrid mixtures of a combustible dust (coal) and a flammable gas (CH_4) were also studied in the 20 litre chamber, using 2500 J ignitors. Data for the low-volatile Pocahontas coal (Poc-1 in Table 3) are shown in Figure 15A, and the high-volatile Pittsburgh coal (Pgh-3 in Table 2) data are shown in Figure 15B. The flammable limits for mixtures of coal and CH_4 are shown by the data points and solid curves. The areas above and to the right of the curves are explosible or flammable and the areas below and to the left of the curves are non-explosible or non-flammable. The data for mixtures of Pittsburgh coal and CH_4 in Figure 15B show a linear or near-linear mixing relationship similar to Le Chatelier's law for hydrocarbon gases^{40,44}. All of the solid circle data are for 2500 J ignitors. The repeatability of the measured dust MEC values is approximately $\pm 10\text{ g m}^{-3}$ in Figure

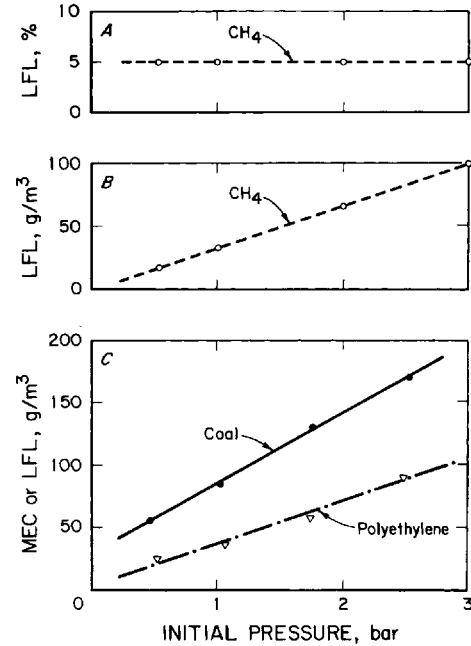


Figure 14 Effect of pressure on the explosibility of Pittsburgh coal, compared to polyethylene dust and methane gas

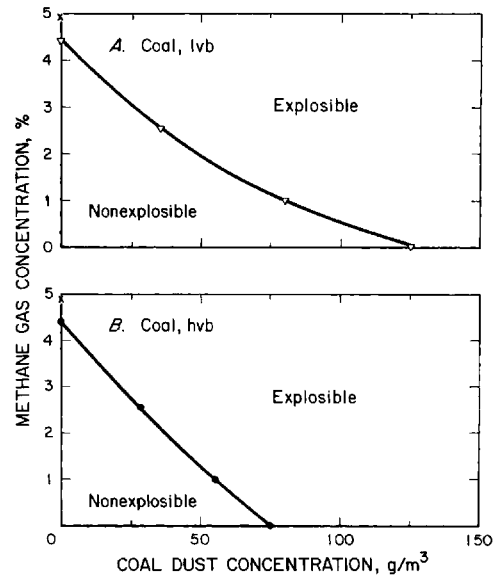


Figure 15 Minimum explosible concentrations of hybrid mixtures of coal dust and methane gas

15. The measured LFL for the pure CH_4 with this 2500 J ignitor is 4.4%, but this is an overdriven system as shown by tests in a larger 120 litre chamber¹⁰. The more appropriate LFL for CH_4 is the 4.9% value measured with a 1000 J ignitor in the 20 litre chamber and shown as the symbol x in the figure. The data for Pocahontas coal and CH_4 in Figure 15A show some curvature. This is probably due to the even greater difference in ignitability between the low-volatile coal and the CH_4 , i.e.

the dust becomes more easily ignited as more CH₄ is added. Therefore, the curvature is more likely an effect of ignitability rather than an effect of flammability. Ideally, the true mixing relationship would be determined in a much larger chamber, such as a 1 m³ chamber, where a very strong ignition source could be used for the dusts without overdriving the CH₄ gas. For most practical situations for mixtures of hydrocarbon dusts and gases, the linear mixing law of Le Chatelier would be sufficient. The approximately linear relationship for the lean limits of dust and gas mixtures was also observed by Amyotte and others^{35,36} using 5 kJ ignitors in a 26 litre chamber.

In the mining industry, coal dust explosions are prevented by the addition of inert limestone rock dust to the deposited coal dust. Therefore, the inerting of coal dust by the addition of limestone rock dust was also studied in the laboratory chamber, and the results were compared to those from full-scale experimental mine tests. Figure 16 shows data on the amount of limestone rock dust required to inert various sizes of Pittsburgh (hvb) and Pocahontas (lvb) coals from Tables 2 and 3. The vertical axis shows the amount of rock dust in the coal and rock dust mixture. The horizontal axis is the mass median particle diameter of the coals. For these tests, regular limestone rock dust was used instead of the fluidized rock dust used for previous USBM laboratory studies^{13-15,17-19}. The limestone rock dust had 75% minus 200 mesh and $D_{med} = 25 \mu\text{m}$. The measurements were made in the 20 litre chamber using 5000 J ignitors. The stronger ignitors were used for the inerting tests because the heavily inhibited, high dust concentrations were intrinsically more difficult to ignite. At each rock dust percentage, tests were run over a wide range of coal dust concentrations (usually 200–800 g m⁻³) to determine the worst case. Tests were made in rock dust increments of 5% and the final amount to inert was interpolated for the values reported in the last row of Tables 2 and 3 and the data shown in Figure 16. For each size of coal dust, more rock dust is required to inert the high-volatile Pittsburgh coal than is required for the low-volatile Pocahontas coal. As with other aspects of explosibility, the finer sized dusts are the more hazardous, requiring more rock dust in the mixture to be inerted. In some cases, the effect of particle size dominates over volatility as the finer sizes of Pocahontas coal require more rock dust than the larger sizes of Pittsburgh coal. The data reported here are consistent with those

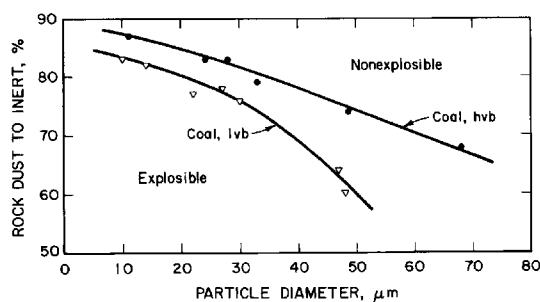


Figure 16 Inerting of high-volatile Pittsburgh and low-volatile Pocahontas bituminous coals by limestone rock dust as a function of coal particle size

reported by Amyotte and others⁴⁵ from tests in a 26 litre chamber.

A comparison of USBM experimental mine and 20 litre laboratory limestone rock dust inerting data for various coal dusts is shown in Figure 17. The vertical axis shows the amount of rock dust in the mixture necessary to inert the coals. The horizontal axis is the moisture-ash-free volatility of the coals. The data are for various bituminous coal dusts from low to high volatility. The dashed line is a summary of previous inerting tests^{31,32,46} of various pulverized coals in the USBM Bruceton Experimental Mine (BEM). The solid line is a summary of recent data^{15,47} for pulverized coals from the USBM Lake Lynn Experimental Mine (LLEM). The filled circles are 20 litre laboratory data for coals dusts with mass median diameters of 40–50 μm , similar to the sizes of the coals tested in the BEM and the LLEM. The open circles are 20 litre data for finer sized coals with $D_{med} = 20\text{--}35 \mu\text{m}$. The uncertainties in the mine and laboratory data are of the order of $\pm 3\%$ rock dust content. The laboratory and experimental mine inerting data are also consistent with those from the German Experimental Mine Tremonia^{48,49}. There is a general trend that the LLEM tests show a somewhat higher rock dust inerting requirement than the BEM data or the laboratory chamber data for the same sized coals. However, the laboratory data do show sufficiently good agreement with the mine data such that the 20 litre chamber can be used for preliminary testing before full-scale mine testing and to study a much wider range of coal sizes and volatilities than could be done in the experimental mines.

Conclusions

The data reported in this paper show that the USBM 20 litre laboratory chamber is useful for studying a wide range of explosion characteristics of coals and that the data show reasonably good agreement with those from large-scale tests in the experimental mines. Data for various coals show that higher volatile coals and finer sized coals are more hazardous. Because of the importance of particle size, it is critical that representative samples of dusts be collected for explosibility evaluation.

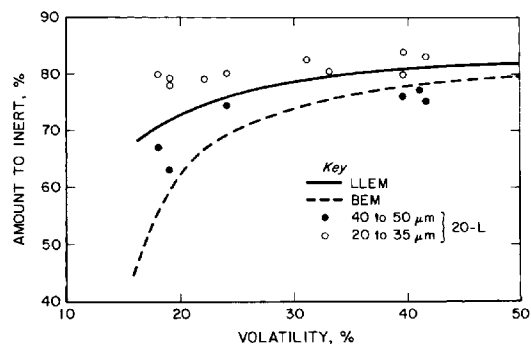


Figure 17 Rock dust inerting requirements for coal dusts of different volatilities, showing comparison between 20 litre laboratory chamber data, Lake Lynn experimental mine (LLEM) data, and Bruceton experimental mine (BEM) data

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Nomenclature

\bar{D}_g	Geometric mass mean diameter (μm)
σ_g	Geometric standard deviation
D_{med}	Mass median diameter (μm)
D_s	Arithmetic surface mean diameter (μm)

\bar{D}_w	Arithmetic volume or mass mean diameter (μm)
dP/dt	Rate of pressure rise (bar s^{-1})
$(dP/dt)_{max}^{1/\lambda}$	Normalized maximum rate of pressure rise (bar ms^{-1})
P_{ex}	Maximum explosion pressure (bar (a))
T	Transmission (%)
V	Vessel volume (m^3)