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Arch. Min. Sci. **63** (2018), 3, 713-726

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/123693

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EXPLOSIVE DUST TEST VESSEL COMPARISON USING PULVERIZED PITTSBURGH COAL

PORÓWNANIE URZĄDZEŃ TESTUJĄCYCH TENDENCJE PYŁU WĘGLOWEGO DO WYBUCHU Z WYKORZYSTANIEM ROZDROBNIONEGO WĘGLA Z KOPALNI W PITTSBURGU (USA)

Explosions of coal dust are a major safety concern within the coal mining industry. The explosion and subsequent fires caused by coal dust can result in significant property damage, loss of life in underground coal mines and damage to coal processing facilities. The United States Bureau of Mines conducted research on coal dust explosions until 1996 when it was dissolved. In the following years, the American Society for Testing and Materials (ASTM) developed a test standard, ASTM E1226, to provide a standard test method characterizing the "explosibility" of particulate solids of combustible materials suspended in air. The research presented herein investigates the explosive characteristic of Pulverized Pittsburgh Coal dust using the ASTM E1226-12 test standard. The explosibility characteristics include: maximum explosion pressure, (P_{max}); maximum rate of pressure rise, $(dP/dt)_{max}$; and explosibility index, (K_{st}). Nine Pulverized Pittsburgh Coal dust concentrations, ranging from 30 to 1,500 g/m^3, were tested in a 20-Liter Siwek Sphere. The newly recorded dust explosibility characteristics are then compared to explosibility characteristics published by the Bureau of Mines in their 20 liter vessel and procedure predating ASTM E1126-12. The information presented in this paper will allow for structures and devices to be built to protect people from the effects of coal dust explosions.

Keywords: coal dust, coal dust explosion, ASTM E1226, Pittsburgh coal

Wybuchy pyłu węglowego są jednym z głównych zagrożeń związanych z bezpieczeństwem pracy w górnictwie węgla. Wybuchy i spowodowane przez nie pożary skutkują poważnymi zniszczeniami w kopalniach podziemnych, powodować mogą ofiary śmiertelne a także uszkodzić urządzenia do transportu i przeróbki węgla. Instytut Górnictwa w USA (The United States Bureau of Mines) prowadził badania nad wybuchami pyłu węglowego do roku 1996, kiedy to Instytut został rozwiązany. W kolejnych latach Amerykańskie Stowarzyszenie Badań Materiałów (ASTM) opracowało normę ASTM E1226, określającą standardową metodę badania w celu określenia skłonności do wybuchu części stałych substancji palnych zawieszonych w powietrzu. W pracy przedstawiono badania właściwości wybuchowych pyłu węglowego z rozdrobnionego węgla z kopalni w Pittsburgu w oparciu o metodę określoną w dokumencie normatyw-

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nym ASTM E1226-12. Charakterystyka skłonności pyłu do wybuchu obejmuje następujące parametry: maksymalne ciśnienie wybuchu (P_{max}), maksymalne tempo wzrostu ciśnienia ($(dP/dt)_{max}$), oraz wskaźnik (K_{st}) określający skłonność pyłu do wybuchu. Do badań wykorzystano dziewięć próbek różniących się stężeniem pyłu węglowego (od 30 do 1500 g/m^3). Badania przeprowadzono z wykorzystaniem 20-litrowej komory w kształcie kuli. Otrzymane charakterystyki porównano następnie do charakterystyk opublikowanych przez Amerykański Instytut Górnictwo po przeprowadzeniu badań z użyciem 20-litrowej komory będącej na wyposażeniu Instytutu oraz w oparciu o procedury stosowane przed wprowadzeniem normy ASTM E1126-12. Informacje zebrane w niniejszej pracy pozwolą na opracowanie konstrukcji i urządzeń które skutecznie będą mogły chronić ludzi przed skutkami wybuchów pyłu węglowego.

Słowa kluczowe: pył węglowy, wybuch pyłu węglowego, ASTM E1226, węgiel z kopalni w Pittsburgu

1. Introduction

In the United States, coal dust explosions have historically exceeded 600 deaths per year with some incidents claiming 200 or more lives (Humphrey, 1960). The threat of coal dust explosions still exists within the coal industry. Fatal coal mine explosions since 2001 include; No. 5 Mine (13 killed, 2001), Sago Mine (12 killed, 2006), Darby Mine No. 1 (5 killed, 2006), and Upper Big Branch Mine (29 killed, 2010) (NIOSH, 2017). For a dust explosion to occur, several conditions must be met. The dust must be: combustible, suspended in an atmosphere capable to support flame, have a particle size distribution capable of propagating flame, at a concentration that is within its explosibility range and be exposed to an ignition source of sufficient energy to initiate combustion (Echoff, 2003).

Coal dust and its ability to explode when distributed into the air has been a topic of concern for over 300 years. As coal became the power source for the industrial revolution in the early 1700s, the demand and use of coal grew exponentially. By the early to mid-1800's, it was theorized that coal dust could cause or enhance a coal mine explosion. The Royal Commission in 1894, the Prussian Fire-Damp Commission in 1884, and the Commission on Explosions in Mining in 1891, among others, conducted some of the earliest identified research on explosibility of coal dust. By the early 1900s, the English Royal Commission, Taffanel of France, Czaplinski and Jicinsky in Austria had concluded that coal dust could support an explosion without the support of methane (Rice, 1911; Cybulski, 1975).

The United States Congress appropriated funds for the Federal Geological Survey to begin an investigation of mine explosions in 1907 after a series of eighteen-coal mine disasters occurred in the United States within a year. The worst two disasters in 1907 occurred within two weeks of each other in December at Monongah and Darr Mines, killing over 600 people (Humphrey, 1960). By 1910, the United States Bureau of Mines (USBM) was created and tasked with continuing mine explosion research. The research was done with a great deal of collaboration with Poland and other European countries with a bi-annual conference taking place in Warsaw (Cybulski, 1975). In addition to full-scale testing, the USBM developed methods of testing coal dust explosibility in a laboratory setting. These included the Pittsburgh Research Laboratory 20-Liter test vessel (PRL 20L), a 1-m^3 chamber, and the 1.2-liter vessel known as the Hartmann tube apparatus. The USBM quantified coal dust explosibility as a function of the maximum explosion pressure (P_{max}), the maximum rate of pressure rise $(dP/dt)_{max}$, and explosibility index (K_{st}), collected from years of research with Pulverized Pittsburgh Coal (PPC) (Breslin, 2010; Cashdollar et al., 1993; Cashdollar, 2000). The USBM was disbanded in 1996 by the United States Conrgress and President Bill Clinton because of waning public support and decreased political clout (Breslin, 2010).

The American Society for Testing and Materials (ASTM) was founded in 1898. The ASTM organization dedicated itself to "the development and unification of standard methods of testing; the examination of technically important properties of materials of construction and other materials of practical value, and also to the perfection of apparatus used for this purpose" (ASTM, 1998). In 2000 the ASTM developed test method E1226 (ASTM E1226) to provide a standard test method characterizing the "explosibility" of particulate solids of combustible materials suspended in air (ASTM E1226-12a, 2012).

A material's explosibility is characterized with quanantative data with the variables denoted as the P_{max}, $(dP/dt)_{max}$, and K_{st} values. In 1985, Cashdollar presented these variables being used by the USBM for the evaluation of coal dust. These same variables are utilized by ASTM for similar purposes in ASTM E1226. The data provided by the USBM was generated before the creation of ASTM E1226. To the authors' knowledge, an evaluation on PPC dust has not been conducted following ASTM E1226 and been widely distributed. The current ASTM test standard may have an impact on the dust explosion characteristics P_{max}, $(dP/dt)_{max}$ and K_{st}.

This paper will re-examine the explosibility of PPC varying the dust concentrations within a 20-liter vessel according to ASTM E1226 using a Siwek 20-Liter Sphere. The maximum mean value of peak pressure and explosive index are reported as P_{max} and $(K_{st})_{max}$. The recorded P_{max} and K_{st} for PPC were compared to results published by the USBM in 1985.

1.1. Properties that Influence Dust Explosibility

Physical properties of dust and their dust clouds affect the explosibility and explosion magnitude of an explosive dust reaction event. Echoff (2003) discusses how particle size, dust concentration, turbulence and other properties affect the characteristics of a dust explosion. The influence of the properties are summarized in Table 1.

TABLE 1

Dust properties and their effect on explosibility characteristics (Echoff, 2003)

Particle Size	**Decreases P_{max}, $(dP/dt)_{max}$, and K_{st}**
Dust Concentration	Increases P_{max}, $(dP/dt)_{max}$, and K_{st} until peak pressure is reached then Decrease
Turbulence	Increases P_{max}, $(dP/dt)_{max}$, and K_{st}
Moisture	Decreases P_{max}, $(dP/dt)_{max}$, and K_{st}
Initiation Pressure	Increases P_{max}, $(dP/dt)_{max}$, and K_{st}
Initiation Energy	Increases P_{max}, $(dP/dt)_{max}$, and K_{st}

Dust properties have a potential influence on dust explosibility and are of critical importance to this research. Therefore, these variables were monitored throughout the research to ensure the control variables did not confound the data. The dust was changed in a controlled and incremental manner to follow ASTM E1226 guidelines.

1.2. United States Bureau of Mines Coal Dust Tests

In the 1980's, the USBM conducted a series of coal dust explosion tests utilizing their internally designed PRL 20L chamber. The USBM used pulverized coal dust from a Pittsburgh coal seam. Pittsburgh coal is a name given to a thick, continuous and wide spread coal bed located in Pennsylvania, West Virginia, Ohio, and Maryland covering an area over 13,000 km^2 (5,000 mi^2) (Tewalt, et al. 2001). The standard PPC dust used by the USBM was described as being 80% minus 200 mesh (<75 μm), 13% minus 20 μm and a median particle diameter of 48 μm. The proximate analyses of Pittsburgh coal is summarized in Table 2.

TABLE 2

Proximate analyses of Pittsburgh Coal (Cashdollar, 1996)

Moisture (%)	1
Volatility (%)	37
Fixed Carbon (%)	56
Ash (%)	6
Heating Value (cal/g)	7720

All tests were conducted at an ignition pressure of 1-atm by using pyrotechnic igniters of 2.5 kilojoule (kJ) to initiate the coal dust explosions (Cashdollar et al., 1985). Figure 1a shows the K_{st} data with values increasing with increased dust concentrations until approximately 300 to 500 g/m^3. As the dust concentration increases, the variability of K_{st} increases. Figure 1b is a plot of the peak pressure measured at different dust concentrations. As the concentration increases, the $P_{\max}$ increases. In Figure 1b, the pressure ratio increases rapidly to approximately 6.5 bar between dust concentrations of 0-300 g/m^3. However, around 300 g/m^3 the trend changes and the pressure remains relatively constant as dust concentration increases further. Variability of the testing results is difficult to discern. From the data published it appears that only the dust concentrations below 250 g/m^3 were repeated along with 500 g/m^3.

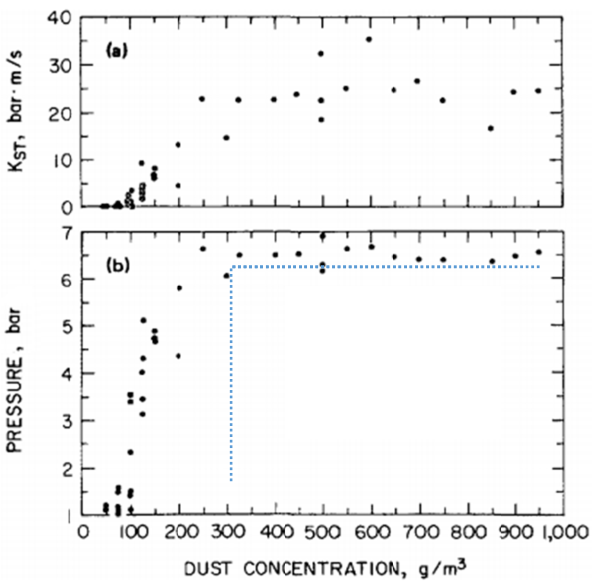

Fig. 1. Explosibility Data for Pittsburgh Coal Dust, modified from (Cashdollar et al., 1985)

Cashdollar (1996) furthered the USBM's research on the explosibility of coal dust by examining the influence of coal volatility, particle size, oxygen concentrations, and amounts of limestone rock dust to inert the coal dust using the PRL 20L (Cashdollar, 1996). Cashdollar also expanded coal dust concentration vs. explosion pressure curve to concentration levels of coal dust as seen Figure 2.

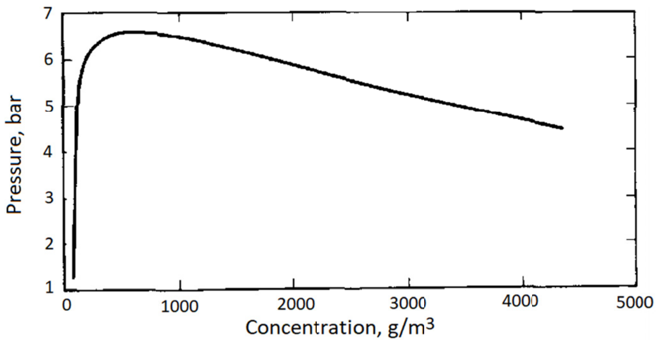

Fig. 2. Expanded Explosibility Data for Pittsburgh Coal Dust, modified from (Cashdollar, 1996)

The extended explosibility data was conducted in a wider range of PPC dust concentrations. The highest concentration shown in Figure 2 was in excess of 4000 g/m^3 while Figure 1 did not exceed a dust concentration of 1000 g/m^3. The plot in Figure 2 shows a rapid increase in pressure as the concentration increases and reaches a peak pressure around a dust concentration of 600 g/m^3. After the peak in pressure, the trend decreases in a linear fashion. The trend line in Figure 2 matches the data shown in Figure 1 fairly well, within the limits of dust concentrations shown in Figure 1. The trendline in Figure 2 has no error bars or viability shown.

1.3. ASTM Standard E1226

The purpose of the American Society for Testing and Materials (ASTM) E1226 test method is to provide standard test methods for characterizing the explosibility of fine material evenly distributed in the air as a dust cloud. The test method is applied to all potentially flammable materials that are 420 microns or smaller in size. Industries producing suspect materials include those processing metals, wood, coal, flour and sugar. The standard first prescribes a procedure to determine if a dust is explosible with a screening test. If the dust is found to be explosible, then the severity of the explosibility is determined through a series of predetermined tests, based on dust concentration. Dust explosibility characteristics include:

- Explosion pressure (P_{ex}): "The maximum pressure rise produced during a single deflagration test" (ASTM E1226-12a 2012).
- Maximum explosion pressure (P_{max}): "the maximum pressure rise produced during the complete course of deflagration tests" (ASTM E1226-12a, 2012).
- Maximum rate of pressure rise $(dP/dt)_{max}$: maximum value for the rate of pressure increase per unit time reached during the complete course of deflagration tests. (ASTM E1226-12a, 2012).

- The deflagration index (K_{st}): a parameter to designate explosive severity. It is extensively used in the design for explosion vents and explosion suppression system. (K_{st}) is obtained using Equation 1:

$$K_{st} = (dP/dt) * V^{1/3}, \text{ where } V \text{ is vessel volume in m}^3 \tag{1}$$

ASTM E1226-12A is typcially conducted within 1-m^3 test vessel or a smaller vessel like the Siwek 20-Liter Sphere. Due to the volume and mass differences of the two different sized vessels, a mathematical formula is specified within ASTM 1226 to compensate for the cooling effect the walls of the Siwek 20-Liter Sphere have on explosions. A mathematical correction (P_m) is performed on the measured P_{ex}. The equation for the correction is taken from the Appendices of ASTM E1226-12A and is shown below.

$$P_m = 0.775\, P_{ex}^{\ 1.15} \tag{2}$$

The maximum mean value of peak pressure, rate of pressure change and explosive index is reported at $P_{\max}$, $(dP/dt)_{\max}$; and $(K_{st})_{\max}$. All pressure readings are corrected with Equation 2 when applicable per ASTM E1226.

1.4. Key differences between Bureau of Mine and ASTM tests

While the USBM and the Siwek 20L Sphere specified in ASTM E1226-12A are similar in volume, there are some key differences between the tests that should be noted. The USBM vessel (PRL 20L) is not completely spherical and utilizes a different dust injection nozzle and methodology as shown in Figure 3. The PRL 20L vessel has the test material loaded at the base

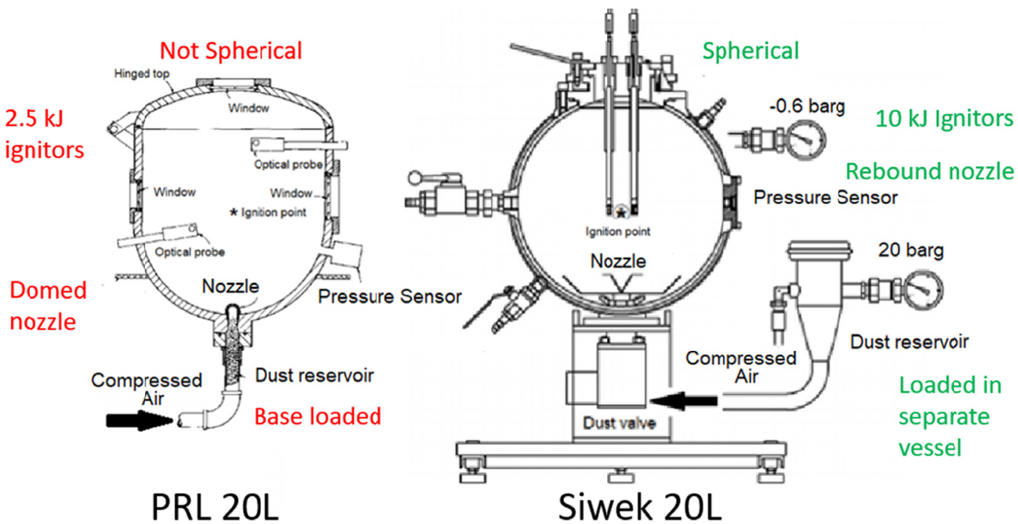

Fig. 3. A Comparison of the USBM PRL 20L on left (adapted from Cashdollar, 1996) and the Siwek 20 Liter on right (adapted from Kuhner AG, 2011)

of the vessel within a distribution nozzle. The distribution nozzle has several orifices that disperse the dust in the chamber. The Siwek 20-Liter Sphere is loaded by placing samples in a separate dust-holding chamber. The dust sample is then injected into the test vessel through an air valve and across a rebound plate system.

Testing within the PRL 20L vessel utilized Sobbe chemical ignitors with a total energy of 2.5 kJ (Cashdollar, 1996). The test conducted by the authors used two Sobbe chemical ignitors with a total energy of 10 kJ which is four times greater than the historic USBM testing. The USBM tests used PPC that was 80% minus 200 mesh (<75 μm) and a median diameter of 48 μm. The authors used PPC that was 39% minus 200 mesh and had a median diameter in between 150-μm and 75-μm size. The larger particle size in the authors' PPC is expected to create lower explosive dust characteristic values than the USBM tests recorded.

Cashdollar (2000) noted the PRL 20L chamber created low levels of turbulence during experimentation. It was stated that at the higher turbulence level recommended in ASTM Standard E1226-12A, the maximum $(dP/dt)V^{1/3}$ and K_{st} data would be roughly three times higher. The increased turbulence helps create a homogenous dispersion of powder within the test vessel. It was also found that more turbulent flow decreases ignition delay and increases the rate of pressure increase through mixing of ignited dust particles, unignited dust particles, and heat generated by the combustion of the dust particles (Bartknecht, 1989).

Research has shown that the Siwek 20L, PRL 20L and 1m^3 chambers generate comparable uniformities of dust dispersion. Particle size reduction was witnessed in the Siwek 20L post dust injection while no reduction was recorded in the other two chambers (Kalejaiye et al., 2010).

There is difficulty in exactly duplicating the test condtions from the USBM's research. The material properites and environmental conditions can not be fully duplicated. Though PPC dust was procured for the recent evaluation, coal is known to vary chemically and physically within the same mine let alone a geographically large bed. The particle distribution and age of the PPC is not fully defined in either the USBM or the recent evaluations.

2. Methodology of determining dust explosion characteristic of PPC

For this research, the test procedure outlined within the 20L Apparatus Manual supplied with the Siwek 20 Liter Sphere was followed (Kuhner AG, 2011). The tests conducted complied with ASTM E1226-12A. In Figure 4, a picture of the Siwek 20 Liter Sphere used for the testing is shown. During an experiment, PPC dust was placed in the dust container and it was pressurized to 20 bar (gauge). The explosion chamber was connected to a vacuum pump and a pre-test pressure level of –0.6 bar (gauge) was set. The PPC dust was distributed from the dust container into the partially evacuated explosion chamber by remote activation of a solenoid valve at the base of the explosion vessel. The resulting dust cloud was ignited with two 5kJ SOBBE (10 kJ total energy) chemical igniters placed at the end of the ignition leads. The igniters were located at the center of the spherical explosion chamber. Two Kistler piezoelectric pressure transducers were used to observe the pressure history from each test. The Siwek 20 Liter Sphere design and operation is greatly influenced by the works of Richard Siwek published in 1976-1980 (Bartknecht, 1989).

The Siwek 20 Liter Sphere was calibrated with niacin as part of the Calibration Round Robin of 2015 (CaRo15) sponsored by Adolf Kuhner AG. The niacin was milled, homogenized

Fig. 4. Siwek 20-Liter Sphere used for testing

and shipped in airtight packages. The niacin was evaluated per the procedure described in the Manual CaRo 15 (Adolf Kuhner AG, 2015). Results from the explosive dust characterization test on the niacin can be seen in Table 3.

TABLE 3

Explosives Characteristics of Niacin from University testing

P_{max}	= 8.4 bar
$(dP/dt)_{max}$	= 923 bars/s
$(K_{st})_{max}$	= 250 bar*m/s.

Adolf Kuhner reported that 62 test laboratories worldwide submitted explosive dust characterization data on the niacin utilized during the Calibration Round Robin of 2015 (Adolf Kuhner AG, 2016). There were 75 unique evaluations on the niacin, which resulted in reference values for P_{max} and K_{st} as shown in Table 4. The University's evaluation of the supplied niacin is within the published reference values. The Siwek 20 Liter sphere is assumed to be calibrated and results acceptable.

TABLE 4

CaRo 15 reference values (Adolf Kuhner AG, 2016)

P_{max} (bar)	= 8.2 +/– 10%	7.3 … 9.0 bar
$(K_{st})_{max}$ (bar*m/s)	= 245 +/– 10%	220 … 269 bar

The distribution of the PPC used was evaluated by following ASTM Standard D197-87, Standard Test Method for Sampling and Fineness Test of Pulverized Coal (ASTM D197-87, 2012). ASTM standard D197 – 87 utilizes a standard set of sieves to create eight distinct size classifications. The results from this test can be seen in Table 5.

TABLE 5

Results from ASTM D197-87 analysis of PPC

% Retained	Cumulative % Retained	Cumulative % Passing	Sieve size	Sieve (um)
0%	0%	100%	8	2360
0%	0%	100%	16	1180
0%	0%	100%	30	600
4%	4%	96%	50	300
27%	30%	70%	100	150
31%	61%	39%	200	75
15%	76%	24%	325	45
24%	100%	0%	325+	45-

The University PPC had a particle distribution with 39% minus 200 mesh and had a median diameter in between 150-µm and 75-µm size. The USBM tested coal with 80% minus 200 mesh and the median diameter was 48 micron.

Dust samples were not sifted, sorted, or processed to change particle size or shape. To minimize particle size variation, all test samples were pulled from the same container of PPC. The container of PPC was blended using a shaker-mixer technique in an effort to minimize particle segregation that may have occurred during shipping. Dust humidity levels were below 10% and kept consistent by storing all samples and material in sealed containers. The tests were conducted in an environmentally controlled laboratory with an ambient air temperature of 21 degrees Celsius (C). All testing was conducted with the same bottle of normal compressed air that had a tank pressure greater than 40 bar. The temperature and flow of the water flowing through the 20 Liter Siwek Sphere water jacket was verified to be within specifications (<25°C, and >0.5 liter/minute). To control the effects of turbulence, the ignition delay time is standardized for the 20 Liter Siwek Sphere at 60 milliseconds (Kuhner AG, 2011).

The test procedure outlined within the Siwek 20L manual (Kuhner AG, 2011) recommends an initial test series with dust masses and concentrations as seen in Table 6. The first test series starts at a low dust concentration of 60 g/m^3 and increases in steps to a high dust concentration of 1500 g/m^3. This is so the maximum value for the explosion pressure (P_{ex}), and the rate of pressure increase, $(dP/dt)_{ex}$, can clearly be determined.

TABLE 6

Dust mass and concentration recommended for testing in Siwek 20-Liter Sphere (Kuhner AG, 2011)

Coal Dust Mass (g)	1.2	2.5	5.0	10	15	20	25	30
Coal Dust Concentration (g/m^3)	60	125	250	500	750	1000	1250	1500

Test series two and three are conducted for replication. The replication of data is used to validate the complete dust evaluation. The P_{ex} for each dust concentration level has a mean value calculated. If the $P_{\max}$ from any of the three test series deviates more than 5% from the mean of the three test series, then the dust evaluation is invalid. If the $(dP/dt)_{ex}$ or K_{st} from one test series deviates more than 20% from the mean of the three test series, then the dust evaluation is invalid. For this paper, the maximum mean value of peak pressure, rate of pressure change and explosive index is reported as $P_{\max}$, $(dP/dt)_{\max}$, and $(K_{st})_{\max}$.

3. Results and discussion

An overview of the data collected during testing can be seen in Figure 5. All concentrations passed the criteria set in ASTM 1226-12A where the P_m and the K_{st} should not deviate from the mean value for each concentration by 5% and 20% respectively.

From the data collected during the research, the P_m, corrected P_{ex} from Equation 2, trends upward with increasing dust concentrations until a concentration of 250 g/m^3. The rise in the P_m between dust concentrations of 200 and 500 g/m^3 is relatively flat. Beyond the dust concentration of 500 g/m^3, it can be seen that P_m corrected trends downward. The K_{st} data has more variability and a trend is more difficult to discern. The $(dP/dt)_{ex}$ and its corresponding K_{st} values will have more variability due to the nature of the testing conducted. The slightest change in turbulence, mixing, ignitor energy and ignition timing all affect the reaction rate of the dust explosion process as shown in Table 1. A best effort is made to keep the reaction variables constant, however some variation is inevitable.

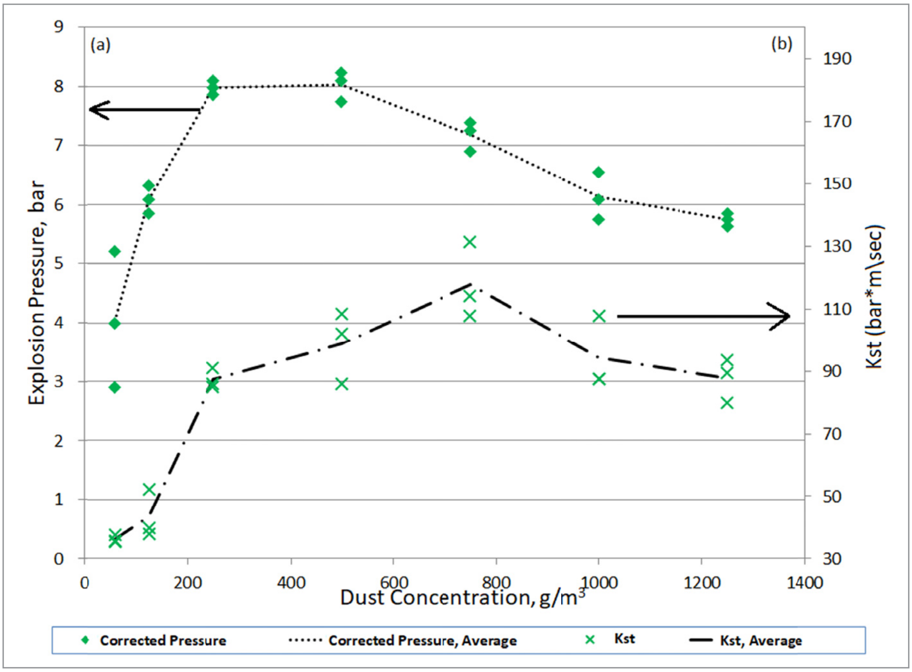

Fig. 5. P_m and K_{st} for PPC dust in University Siwek 20L sphere

By calculating a second order polynomial, it can be seen that K_{st} peaks around 750 g/m^3. The scatter in the data is most likely due to the explosive parameter recorded. Small variations in turbulence and mixing will affect the reaction rate of the explosion. A slight change in the slope of pressure could create a large difference in the maximum rate of pressure increase recorded. K_{st} is based on the maximum rate of pressure increase (dP/dt), so it to would have a corresponding variability.

The maximum explosive parameters from the evaluation of PPC can be seen in Table 7. The P_{max} value of 8.1 bar occurred at a concentration of 500 g/m^3. Whereas the $(K_{st})_{max}$ and $(dP/dt)_{max}$ are reached at a concentration of 750 g/m^3 with values of 118 bar*m/s and 435 bar/s respectively. It is not unusual for P_{max} and $(K_{st})_{max}$ to occur at different dust concentrations (Holbrow, 2009).

TABLE 7

Maximum Explosive Parameters of PPC

	Maximum value	**Dust concentration**
P_{max}	= 8.1 bar	500 g/m^3
$(dP/dt)_{max}$	= 435 bars/s	750 g/m^3
$(K_{st})_{max}$	= 118 bar*m/s.	750 g/m^3

When the results are compared against previously published data from the USBM (Cashdollar et al., 1985), a few differences can be readily seen as shown in Figure 6. Peak pressures recorded in the Siwek 20L are consistently higher until the concentration level of 900 g/m^3 is reached. Higher concentrations resulted in lower peak pressure when compared to the referenced data. The maximum corrected pressure reached in this research was 8.1 bars compared to approximately 6.6 bar reported by the USBM in (Cashdollar, et al. 1985). The trend lines vary a great deal as well. The research presented in this paper shows a more prominent pressure peak developing

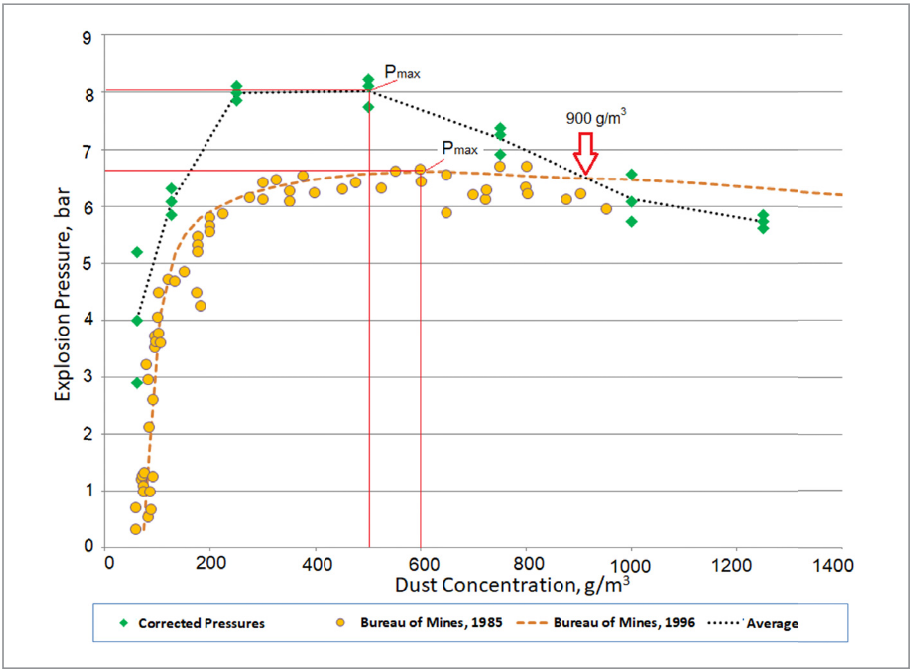

Fig. 6. Explosion Pressure – MS&T Data with Referenced Data (Cashdollar et al., 1985; Cashdollar, 1996)

between concentrations of 250 and 500 g/m^3. Additionally, the slope of decreasing pressure beyond P_{max} descends at a steeper rate than the trend line published by the USBM in 1996 (Cashdollar, 1996). Both data sets are a tight fit to their respective trend lines. The BOM trend line from the (Cashdollar, 1996) appears to be a good fit to the data presented in (Cashdollar et al., 1985), however, it is not explicitly stated that the trend line is related to the previously published data.

The differences in data trends shown in Figure 6 may be due to a couple factors. The ASTM standard study could have higher peak values and a more defined peak pressure for several reasons. 10 kJ chemical igniters that were used during the ASTM standard study compared to the 2.5 kJ ignitors used by the USBM. The Siwek 20 liter vessel creates a more turbulent flow than the USBM PRL 20 liter vessel while increasing the quantity of fine particles during dust injection.

The K_{st}, explosive index, also varies between the USBM published data and the ASTM standard methods shown in Figure 7. The trends are similar, but the recent data has a magnitude of 3-4 times the values seen in the USBM data. A second order polynomial trend line shows a peak K_{st} in the USBM data of around 30 bar*m/s. This is somewhat expected as Cashdollar (2000) states, "*Note that the turbulence level was lower in the PRL 20L chamber for these tests than that recommended in ASTM E1226. At the higher turbulence level recommended in ASTM Standard E1226, the maximum (dP/dt)*$V^{1/3}$, K_{st} *data for this Pittsburgh coal would be roughly three times higher.*"

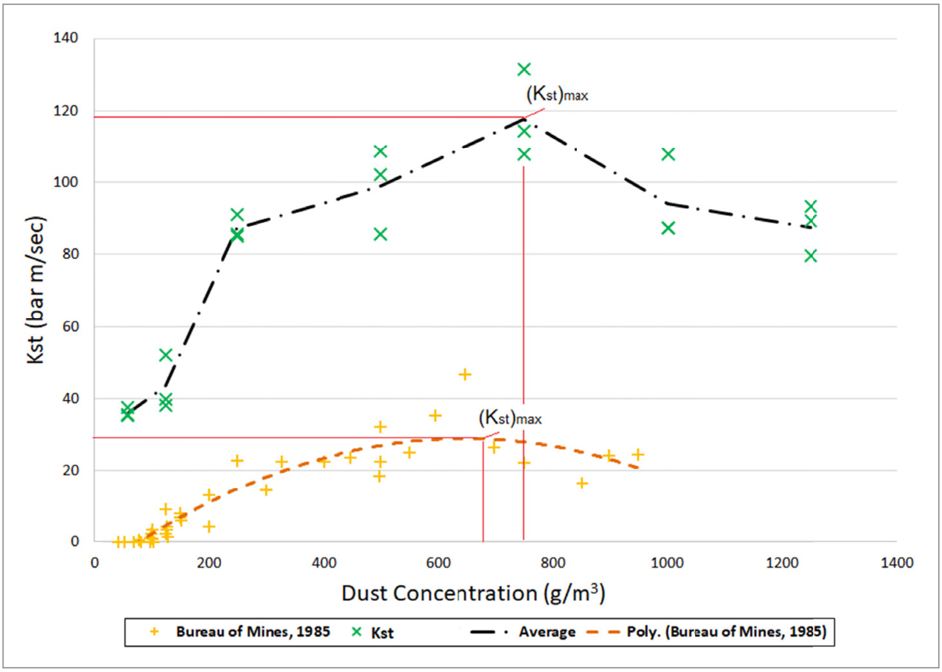

Fig. 7. Explosion KST – University Data with Referenced Data (Cashdollar, 1996)

It was expected that the latest data would trend lower in all dust explosion characteristics compared to the USBM published data due to the larger PPC particle size present in the University tests. If the authors had finer PPC, it is plausible that the P_{max}, $(dP/dt)_{max}$ and K_{st} could all be higher than those recorded during testing. There is difficulty duplicating the exact properties used by the USBM

4. Conclusions and considerations

Coal dust explosions are a major safety concern within the coal mining industry. The explosion and following fires caused by coal dust can result in significant property damage, loss of life and damage to coal processing facilities. The information presented in this paper can be directly compared to industry standards and applied to explosion mitigation engineering practices.

The standard coal for dust explosibility in the mining industry is Pulverized Pittsburgh Coal dust, but a standard test of this material based on ASTM standards had not been conducted since published in 2000. The inability to locate any widely published data on the explosibility evaluation of PPC dust following ASTM E1226 lead such an evaluation.

During the evaluation, a mean maximum pressure of 7.7 bar was calculated during the explosibility testing of PPC dust. The correction equation supplied in ASTM E1226 results in a corrected maximum pressure (P_{max}) of 8.1 bar. This is much higher than the P_{max} value of approximately 6.6 bar published by the Bureau of Mines.

The maximum rate of pressure change, (dP/dt), was 435 bars/s with a resulting K_{st} maximum of 118 m bar/s. The trends of K_{st} values are similar between the USBM data and the ASTM data. The USBM has a peak K_{st} of around 30 bar*m/s while the ASTM study values are magnitude of 3-4 times the values seen in the USBM data.

This data found by the authors using the ASTM standard resulted in P_{max}, and $(K_{st})_{max}$ explosibility characteristics for PPC dust are all greater than those previously published by the USBM. The differences between the USBM and ASTM E1226 testing parameters have a clear influence on the data. The most notable differences include vessel geometry, dust injection method, turbulence, and initiator output energies. The higher turbulence and initiator energy used in the 20L Siwek sphere could explain the in higher explosibility characteristic values in the recent PPC dust evaluation. Due to the time between the original USBM testing and the 20L Siwek testing presented in this paper, it is difficult to exactly duplicate all properties of the PPC dust evaluated. Future testing will further examine the differences between the two test vessels and their testing procedures both chambers will be used to evaluate PPC dust in the same test series.

These findings could have a direct impact on the design of refuge chambers, mine stoppings, and explosion mitigation systems. The material used in this study was coarser than what was reported by USBM. One could expect slightly higher rates of change and explosive index values with the finer dust used by the USBM. It is recommended that higher dust concentrations also be evaluated to see how they correspond with published information based on initial evaluations following ASTM E1226-12A.

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