TECHNICAL DEVELOPMENT OF THE COAL DUST EXPLOSIBILITY METER

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Abstract

The Pittsburgh Research Laboratory (PRL)[1] of the National Institute for Occupational Safety and Health (NIOSH) in collaboration with the Mine Safety and Health Administration (MSHA) Technical Support Center has devised a prototype hand-held instrument which can provide a direct assessment of the potential explosibility of a coal and rock dust mixture.

Current Federal regulations require that rock dust be applied in all underground areas of a coal mine to mitigate the propagation of a coal dust explosion. To determine compliance with the Federal regulation, mine inspectors collect dust samples from sections of underground coal mines for an MSHA laboratory analysis of incombustible content. However, the laboratory analysis may not be completed for more than a week or two, during which time the mine area from which samples are taken may be inadequately protected.

The operation of the Coal Dust Explosibility Meter (CDEM) is based on the difference in optical reflectance between light rock dust and dark coal dust. For a given coal volatility, the optical reflectance of such mixtures is relatively constant at the limit of explosibility, independent of the coal dust particle size. The CDEM is not intended to replace the current MSHA laboratory analysis of coal mine dust samples for incombustible content, but to serve as a supplemental device for enhancing mine safety through improved rock dusting practices.

Introduction

Despite the worldwide research on coal mine safety, coal dust explosions involving fatalities and injuries still occur each year. Research by the U.S. Bureau of Mines (USBM) and agencies in other countries has shown that mixing a sufficient quantity of inert rock dust with coal dust will prevent explosions. U.S. Federal law 30 CFR, 75.403 mandates that the nation's coal mines maintain a total incombustible content of at least 65 percent in non-return entries and at least 80 percent in the return airways where potential for accumulation of finer float coal dust is greater. The 65% total incombustible content is based on a fairly coarse "mine-size dust," a term used often in coal dust explosion research. It was adopted about 1925 and refers to coal dust all of which passes a U.S.A. Standard No.20 sieve (841 micron) and contains 20 percent minus 200-mesh (74 micron) particles. The justification for adopting it is given in Bureau of Mines Technical Paper 464 (Rice et al 1929). Information on the size of dust in mines was obtained by collecting representative samples from passageways not rock-dusted and subjecting them to screen analysis.

Reported in Technical Paper 464, dust collected from ribs, roof, and timbers were the finest, and 40% to 70% of the material passed a 200-mesh sieve. Floor dusts were much coarser, and samples contained 5% to 40% of material passing through a 200-mesh sieve. The sizes were found to vary considerably between points in a single mine, and the quantity of dust also varied. The averages were weighted and for 80% of the mines the final values ranged from 15% to 25% through 200-mesh. Averages higher than 25% were found occasionally and those below 15%, rarely. The dust used in explosion tests was of the standard size nearest to or next finer than the weighted average for the mine furnishing the coal. Thus, dust having 20% through 200-mesh was used most in explosion-hazard investigations and in determining the current 65% total incombustible requirement for intake roadways.

To comply with regulations, mine personnel periodically dust the mine interior with an inert material, such as pulverized limestone (rock) dust. In determining compliance with the law, inspectors for the Mine Safety and Health Administration (MSHA) periodically collect samples of deposited dust from different areas in a mine. In making a determination as to whether samples are to be collected, visual inspection is often used. Typically, poorly rock-dusted areas along a mine entry appear dark, and well rock-dusted areas appear light. When samples are collected in any given mine, they are usually collected at intervals of 500 feet of entry. The preponderance of samples collected are relatively dry (< 1 % surface moisture). The inspector screens the samples through a 10-mesh sieve and sends about 200 grams of the sieved sample to MSHA's facility in Mount Hope, West Virginia for laboratory analysis.

Laboratory analysis at Mt Hope [Montgomery 2005], consists of passing the sample through 20 mesh sieve (841 micron) to remove material larger than 10 mesh and then oven drying the minus 20 mesh material for one hour at 105°C and recording the weight change. The dried sample is then heated in an oven which is ramped up over 1.5 hours and held at 515°C for about 2.5 hours to burn off the combustible coal fraction, thereby leaving the incombustible ash. The weight of the remaining ash, plus the as-received-moisture, is combined and reported as total % incombustible content (TIC). In general, the total processing time from sample collection is about two weeks. During this time, a section or sections of a mine may or may not be adequately rock dusted to protect against a coal dust explosion. Also, the laboratory gravimetric analysis does not take into account the effect of particle size on the explosibility of dust samples. For example, given two mine samples containing 65% TIC, one of which contains 20% of coal mass distributed in particles sizes less than 200 mesh and the other contains 40% of coal mass less than 200 mesh, both are in compliance with the law based on gravimetric analysis. However, in full-scale explosion experiments conducted in the Bruceton and the Lake Lynn Experimental Mines with these dusts, the 40 % <200 mesh will propagate while the 20% <200 mesh will not.

This paper presents recent data on the development and evaluation of a digital Coal Dust Explosibility Meter (CDEM). The CDEM is capable of identifying a dust explosion hazard independent of coal particle size. The meter could be used by the mine operator to manage daily rock dusting operations and can also serve as a device to alert mine personnel or mine inspectors to potentially dangerous accumulations of explosible coal dust.

Coal Dust Explosibility Meter

The CDEM consists of an optical probe connected to a small electronics box with a digital display. The principle of operation of the CDEM is based on the measurement of infrared radiation reflected

[1] Disclaimer: The Findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

from the surface of a homogeneous mixture of two powders with different optical reflectance, such as light colored rock dust and dark coal dust. Near-infrared radiation is emitted by a light emitting diode located behind the window of the probe shown in figure 1. When the meter is inserted in the dust mixture, the infrared radiation reflects off the dust's surface and back to the silicon photodiode sensor also located in the optical module. The normalized reflectance, Φ, is related to the mass fraction of rock dust, f_r, in the sample by the following equation:

$$\Phi = (I_x - I_c)/(I_r - I_c) = f_r/(f_r + K\,(1 - f_r)) \qquad (1)$$

where I_x is the intensity of light reflected from a homogeneous coal and rock dust mixture, I_c is the intensity of light reflected from a pure coal dust surface, I_r is the intensity of light reflected from a pure rock dust surface, and K is a constant related to the material densities and mean particle diameters of both the coal and rock dust. Therefore, Φ is the optical reflectance normalized to 100 percent for pure rock dust.

Figure 1. Prototype Coal Dust Explosibility Meter

the coal particles in the mixture. Particle size has a high variability both within and between mines, since size is dependent on factors such as mine type (i.e., longwa1l or continuous miner), pick cutting speed, cut depth and coal type. Size distribution will also vary along mine entries as coarser dust is deposited from ventilation streams closer to the production area, while finer dust is carried farther down the entries. The effect of particle size of coal dust on the explosibility is best illustrated in figure 2, by the incombustible required to arrest explosion propagation from large-scale experiments conducted in both the Bruceton and Lake Lynn Experimental Mines. The curve shows the amount of incombustible required to prevent propagation for coal dust containing 10 to 75 % of particles passing a No. 200 sieve (-74 microns). With 10 % minus 200-mesh, 55 % incombustible is required; with 20% minus 200-mesh, 65% is required; and with 90 % minus 200-mesh, 80 % incombustible is required. This is also the data used to support the current 65% incombustible requirement for intake airways.

To improve rock dusting practices, the U.S. Bureau of Mines (USBM) developed a portable Rock Dust Meter (RDM) based on optical reflectance capable of measuring the concentration of rock dust in dry, homogeneous samples (Sapko and Watson, 1985, Perlee, et al., 1986, Woods, et al., 1988, Sapko et al. 1991). However, since the amount of rock dust required to inert a mixture varies with coal particle size (Cashdollar and Hertzberg, 1985, Cashdollar et al, 1987, Cashdollar and Hertzberg, 1989a, Cashdollar et al 1989b, Nagy 1991), the measurement of the rock dust concentration is not, by itself, sufficient to determine the possible explosion hazard. The RDM was capable of ±2 weight (wt) % accuracy with prepared samples using mixtures of coal and rock dust with known particle distributions. Therefore, to accurately determine the concentration of rock dust in the mixture the RDM had to be calibrated for the particular type and size of rock dust, and the type and size of coal dust.

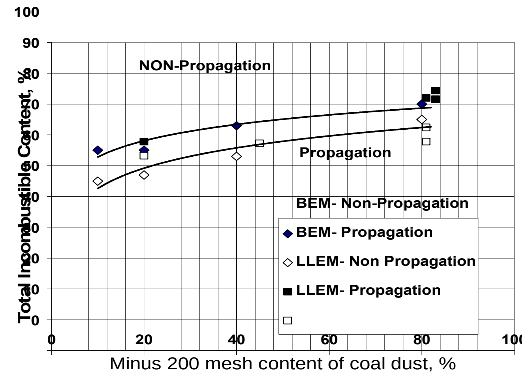


Figure 2 Effect of particle size of coal dust on explosibility.

While examining the data from many coal and rock dust mixtures, it was observed that the normalized reflectance, Φ, measured by the optical reflectance meter, appeared to be constant for a given coal dust at the limit of explosibility, independent of the coal particle size. To help explain this observation, Litton and Chaiken [1996] presented a theory and supporting data that coal dust explosibility and inerting requirements by powdered inhibitors such as rock dust depend upon a material property called the specific absorption which, in turn, relates to the ability of the coal and inert dust to compete for absorption of radiant energy from a source of ignition or propagation. Their theory explains the experimental observation that, at the lower explosion limit, the product of specific absorption and mass concentration of coal dust is constant for fixed coal volatility. Theory and data also support the experimental findings that the RDM may also serve as a CDEM to determine the explosion potential of dust mixture. The CDEM is a simple optical device that measures the relative reflectance from bulk mixtures of coal/rock dust. The ratio of the coal to rock dust specific absorption parameters, as determined by the CDEM, allows for an a priori prediction of the mass fraction of rock dust necessary to inert a particular coal dust. Most importantly, for coal of a fixed volatility, the relative reflectance Φ measured by the CDEM at the inert limit is a constant, independent of particle sizes of the coal dust and rock dust.

To determine Φ, or extinction limit, for Pittsburgh Coal Dust based on experimental full-scale explosion propagation data, mixtures of rock dust with various fractions of minus 200 mesh coal dust were prepared and the test data is shown in figure 2. Air dried coal and rock dust mixtures were prepared at the specific rock dust percentage required to inert as a function of <200 mesh coal dust fraction. The reflectance of this sample was measured by manually inserting the sample in the cup and pressing the sample against the sensor window and recording the reflectance I_x. The reflectance of the pure coal dust, I_c and rock dust, I_r was also measured to determine the normalized reflectance of the mixture, Φ. Since the measured rock dust inerting limit has a precision of approximately ± 3 wt percent, rock dust samples were also prepared at ± 3 wt percent from the inerting limit, and their reflectances also measured. Figure 3 shows the Φ values measured at the inerting limit for the Pittsburgh Coal Dust sizes shown in figure 2. The error bars represent the measured Φ of the samples containing ± 3 wt percent rock dust from the percentage to inert. Therefore, for Pittsburgh coal, Φ at the limit of explosibility is fairly constant over a wide range of particle sizes.

Lucci et al 1995 conducted a similar analysis where Φ value was determined based on extinction limits from tests conducted in the Bureau of Mines 20-L laboratory explosibility chamber for range of coals with different volatilities. The extinction limit Φ was shown experimentally to increase with increasing coal volatility.

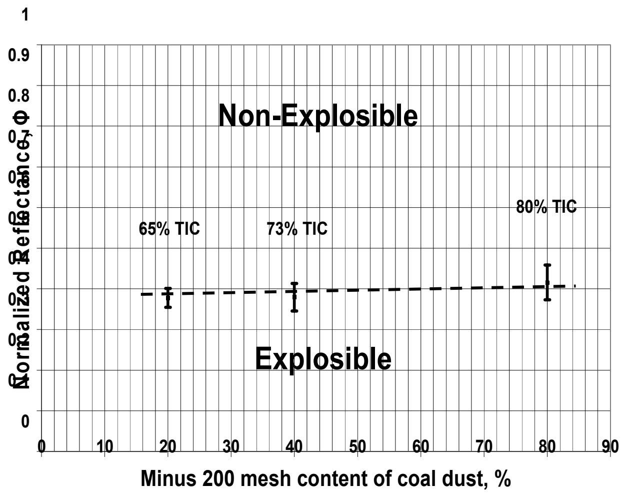


Figure 3. Normalized optical reflectance of Pittsburgh seam coal as a function of particle size of coal.

In practice, the Φ value at which the meter would alert would differ depending on the volatility of the coal seam being mined. The Φ value ranges from 0.3 to 0.4 for 18% and 36 % volatility respectively. The data in figure 4 and supporting absorption theory suggests that the CDEM can be used to indicate the potential explosibility of coal and rock dust mixtures, even if the coal particle size is unknown. While the amount of rock dust needed to inert a mixture increases with decreasing particle size, the normalized reflectance of coal and rock dust mixtures at their limits of explosibility is reasonably constant for a given volatility of coal.

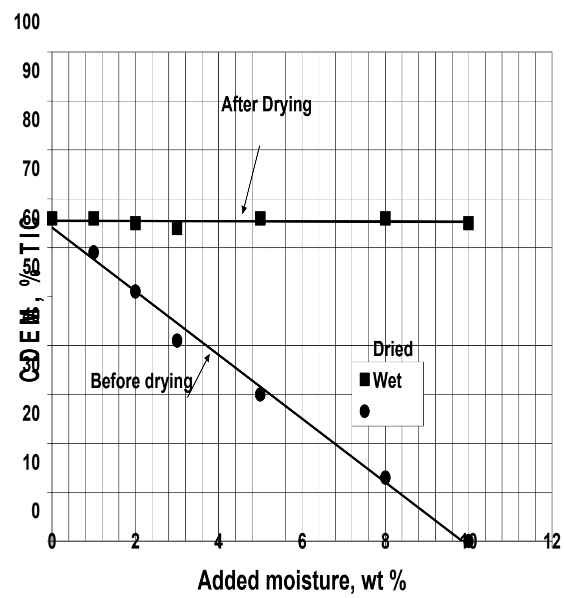


Figure 4. Effect of added surface moisture on the CDEM reading before and after sample drying using molecular sieve.The Effects of Moisture on the Accuracy of the CDEM.

The Effects of Moisture on the Accuracy of the CDEM

Although the meter is capable of ± 3 wt % accuracy using dry samples (< 0.5% moisture), wet or damp samples can have a significant impact on the meter accuracy as shown in figure 4. The presence of added surface moisture changes a sample's reflectivity linearly and quite dramatically with increasing surface moisture. For example 5 % added moisture to a sample containing 65% rock dust and 35 % Pittsburgh Coal dust decreases the CDEM reading from 65% to 30 %. The reading of a damp sample would err on the side of safety indicating the need for more rock dust when in fact the sample may not be explosive or deficient in rock dust. Such results indicate that the meter cannot be used on samples containing over 0.5 % surface moisture. Therefore, to alleviate this problem for in-mine use, NIOSH developed a simple drying technique using a commercially available molecular sieve. Molecular sieve [Davison Chemical Division [2005]*[2] is crystalline, hydrated metal aluminosilicate that is used in the chemical industry for separation of chemical using adsorption. The sieve are manufactured in the form of beads 8 to 12 mesh size with 4 angstroms pore used for general drying applications. The 4 angstrom sieve used in this study was capable of adsorbing 0.2 gram of water per gram of sieve. The sieve behaves as a physical adsorbent. As molecules of water enter the sieve, they are held by physical forces of the Van der Waals type. The sieve can be regenerated for reuse by heating in an oven to 300 °F. For this study the sieve were not regenerated since the cost of regeneration by heating of small samples outweighed the cost of the sieve itself. Drying the sample consisted of placing about 2 grams of damp dust sample with 15 grams of molecular sieve in a capped container and then vigorously shaking the damp dust particles with the sieve material. The sample was allowed to set for 1 minute. After drying the sample contained <0.2 % bound moisture. Then the dried sample was screened through a 20 mesh sieve into the sample cup of the CDEM and a reading was taken. Also shown in figure 4 are the CDEM TIC readings after the samples were dried with molecular sieve. The CDEM reading after drying were all within 2 % of the TIC reading before the water was added. The method of drying with the molecular sieve is a viable approach for handling damp or moist samples within the mine environment.

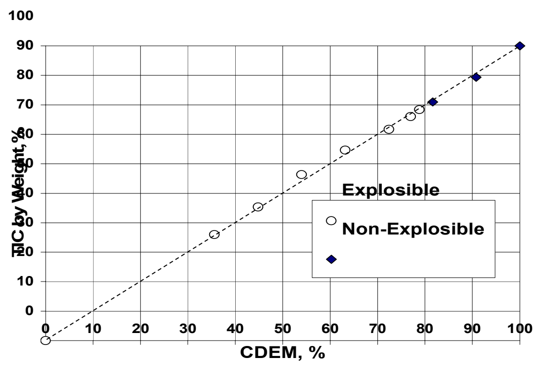
Field Sample Evaluation

The meter was first checked against prepared samples consisting of mixtures of Pittsburgh Pulverized Coal (PPC) dust (80% <200 mesh) and commercially available limestone. Figure 5 shows the results obtained for the PPC mixture after calibrating the meter. The meter readings agree with the actual rock dust concentration to within ±2% rock dust for prepared samples. The meter simultaneously provides an output of either red, yellow or green. Red indicates that the mixture is explosible or needs more rock dust; yellow or borderline indicates further analysis is needed to determine if more rock dust should be added. Green indicates the sample is non-explosive or contains sufficient rock dust to prevent propagation.

In addition to the experimentally prepared sample mixtures using PPC, the CDEM was evaluated using hundreds of samples provided to NIOSH by MSHA's Mt. Hope laboratory. MSHA Technical Support personal coordinated the acquisition mine dust samples collected by mine inspectors from MSHA's Coal Mine Safety and Health Districts 2 and 11. Subsequently the Mt. Hope Laboratory provided to NIOSH a selection of mine dust samples collected by MSHA mine inspectors that were obtained from mines in all MSHA's Coal Mine Safety and Health Districts, except District 1 which covers anthracite mines. Thus, dust samples from various underground coal mines throughout the USA were analyzed with the CDEM and compared to the gravimetric analysis for TIC obtained by the Mt. Hope laboratory for the same samples. Samples from each mine were used to calibrate the meter. Figure 6 shows the CDEM determination of TIC of samples collected from mine A compared with Mt. Hope laboratory

[2] ~~Reference to specific products is for inf~~ormation only and does not imply endorsement by NIOSH

TIC minus the surface moisture. There is more scatter in the data from the actual mine samples than from the prepared sample mixtures. The scatter in the data is probably associated with variations in the coal dust particle diameters contained within the Mine A samples. To confirm this hypothesis of variations in coal particle size from sample to sample, the rock dust was leached from the mixture and a sieve size analysis conducted on the remaining coal dust. The laboratory acid leaching method (1:9 dilute hydrochloric acid) was used to remove the rock dust from the mine dust. The leaching technique was first verified using synthetic mixtures of PPC and limestone dust. Samples of 65% rock dust and 35% PPC were mixed together, and then the rock dust was leached out of the samples. Size analysis of the residues resulting from acid leaching of the synthetic mixtures gave a surface weighted mean diameter D_s of 30 microns and a standard deviation of ±1 micron ($D_s = \sum D^3 \triangle D \ / \ \sum D^2 \triangle D$), yielding good agreement and therefore confidence in the acid leaching method. Several samples collected from Mine A, were leached and particle size analysis conducted on the residue. The average D_s coal diameter from Mine A was 50 microns ± 6 microns.



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samples of Pittsburgh Pulverized Coal dust.

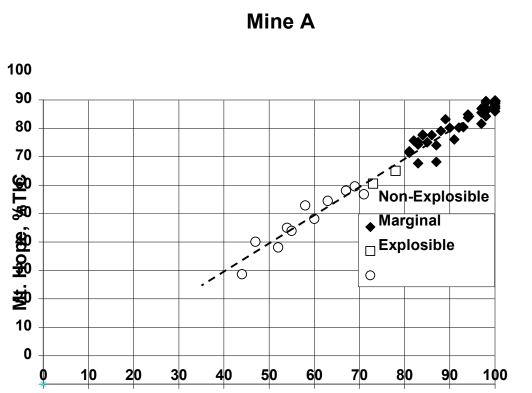

Figure 6. Comparison of TIC and CDEM readings for Mine A dust samples.

Table 1 shows the linear regression statistics from the comparisons of Mt. Hope gravimetric analysis method with CDEM readings for prepared samples, the best mine fit and best combined fit to data from 26 mines. The prepared samples, with the uniform particle size distribution, produced the best fit, as expected, with an R^2 of 0.99 and standard deviation (σ) of 0.8 wt %. While the best agreement with actual mine samples occurred with mine M, R^2 of 0.97 and σ of 2.7 %.

Comparison of Mt. Hope %TIC with CDEM %TIC readings for all mines combined is shown in figure 7. The combined comparison using all mine samples evaluated in this study is quite good with an overall R^2 of 0.92 and σ of 4 % indicating that the meter performed reasonably well for its intended use. To yield the best TIC results, the meter should be calibrated with dry samples of pure rock dust, pure coal dust and an actual dry mine sample containing $\geq$ 63 and $\leq$75 TIC as determined by prior laboratory analysis. The explosibility function of the meter only requires a sample of pure rock dust and pure coal dust for operation.

Table 1. Linear regression data from the comparison of Mt. Hope analysis with CDEM readings

Linear Regression	Prepared samples	Best Mine M	All mines (26)
R^2	0.99	0.97	0.92
Standard Deviation	0.8	2.7	4.0
N	33	58	555
Slope	1.02 ± 0.01	0.97 ± 0.02	0.94 ± 0.01
Intercept	-2.8 ± 0.8	2.6 ± 2.0	5.6 ± 1.0

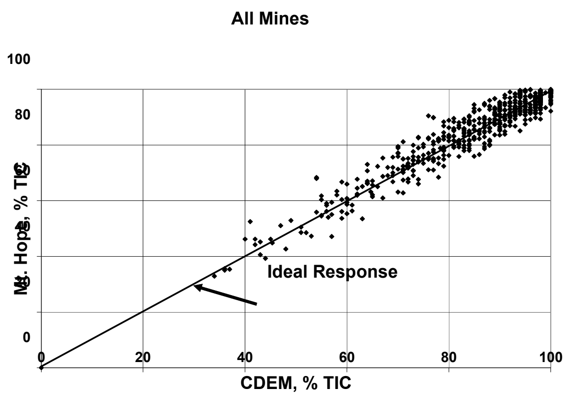

Figure 7. Comparison of % TIC and CDEM readings for all mine dust samples.

Additional work is planned to assess the capability of using the CDEM in some actual operating coal mines by mine inspectors, NIOSH personnel and others. The results of the in-mine studies will be evaluated to determine issues that may hamper the use of the CDEM as another tool for assessing the explosibility hazard of mine dust in a particular area. Work is also in the final stages with respect to obtaining an experimental permit to use the CDEM in underground coal mine areas where methane may be present. The CDEM may also serve as a useful tool to reduce the number of dust samples sent by mine inspectors to the Mt. Hope laboratory for TIC, especially where it can be shown by the CDEM that the TIC is 85 % or higher.

Conclusions

The CDEM has been checked against prepared dust mixtures and found to be accurate to within ± 1 wt percent between 0 to 100 % rock dust. The average measurement error for 26 mines tested was 4.0wt % total incombustible content.

Currently, this hand held, intrinsically safe digital CDEM coupled with a simple drying technique using molecular sieve, could provide an efficient method to determine both the explosibility of the dust and approximate TIC content of dried samples within the mine. The CDEM's in situ explosibility measurement can help mine operators reduce the danger of operating under hazardous conditions of explosible coal dusts and help provide a better balance between the applied rock dust and generated coal dust. Relevant to compliance, an inspector could focus specifically on deficient or borderline samples for subsequent laboratory analysis. Most importantly, the CDEM shows promise as a useful tool for mine operators and safety inspectors for the in situ determination of the explosible nature of coal and rock dust deposits and thereby would enable immediate corrective action.

Acknowledgements

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