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Coal Dust Explosibility Meter Evaluation and Recommendations for Application

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Acronyms and Abbreviations

CD	coal dust
CDEM	Coal Dust Explosibility Meter
CFR	Code of Federal Regulations
ETS	emergency temporary standard
IC	incombustible content
LLEM	Lake Lynn Experimental Mine
LTA	low temperature ashing
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
Φ	normalized reflectance
Φ^*	normalized reflectance at the extinction limit
OMSHR	Office of Mine Safety and Health Research
PPC	Pittsburgh pulverized coal
K	product of rock dust to coal dust particle density ratio and ratio of mean particle diameters of coal to rock dust
RI	Report of Investigations
RD	rock dust
SUT	sample under test
S_c	surface area of coal dust
S_r	surface area of rock dust
TIC	total incombustible content
USBM	United States Bureau of Mines
H_2O	water/moisture

Unit of Measure Abbreviations

ft	feet
f_r	fraction rock dust
g	grams
I_x	light intensity of coal and rock dust mixture
I_c	light intensity of coal dust
I_r	light intensity of rock dust
µm	micrometers or microns
mL	milliliters
mm	millimeters
oz	ounces
% IC	percentage of incombustible content
% CH_4	percentage of methane
% RD	percentage of rock dust
% TIC	percentage of total incombustible content
wt	weight

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Office of Mine Safety and Health Research
National Institute for Occupational Safety and Health

Executive Summary

This report details the results of a NIOSH investigation on the ability of the Coal Dust Explosibility Meter (CDEM) to accurately predict the explosibility of samples of coal and rock dust mixtures collected from underground coal mines in the U.S.[5] The CDEM, which gives instantaneous results in real time, represents a new way for miners and operators to assess the relative hazard of dust accumulations in their mines and the effectiveness of their rock dusting practices. The CDEM was developed by the National Institute for Occupational Safety and Health (NIOSH) and successfully underwent national and international peer review. The intention of the device is to assist mine operators in complying with the Mine Safety and Health Administration (MSHA) final rule 30 CFR* 75.403, requiring that the incombustible content of combined coal dust, rock dust, and other dust be at least 80% in underground areas of bituminous coal mines.

As a final step towards commercialization of the CDEM, and to evaluate the performance of the device as a potential compliance tool, NIOSH undertook an extensive cooperative study with MSHA. This study, completed in 2009–2010, involved field use of the CDEM within MSHA's 10 bituminous coal districts. As part of their routine dust compliance surveys in these districts, MSHA inspectors collected sample coal and rock dust mixtures, field testing these samples for explosibility with the CDEM. Samples were then sent to the MSHA National Air and Dust Laboratory at Mt. Hope, WV, for parallel testing, first using a drying oven to determine the

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[5] The testing was conducted with a prototype version of the CDEM that was available in 2009. The commercial version, CDEM-1000, was released in 2011 and includes improvements in both software and hardware. These improvements are listed in the "Commercial CDEM Development" section and take into consideration many of the MSHA inspector comments detailed in Appendix E.

*Code of Federal Regulations. See CFR in References.

moisture followed by the traditional low temperature ashing (LTA) method. The LTA method determines explosibility of a coal and rock dust sample in a laboratory by heating the mixture to burn off the combustible material. The results, when combined with the moisture, are reported as total incombustible content (TIC). If the TIC is ≥ 80%, the sample is deemed to be nonexplosible and compliant with 30 CFR 75.403.

In the field component of this study, MSHA's use of the CDEM indicated that 30% (175) of the 591 samples collected were explosible. NIOSH was able to obtain and remeasure 297 samples, and 97% of those identified by the CDEM as being explosible (27% of samples) or nonexplosible (73% of samples) correlated with the results of the subsequent lab analysis using the LTA method. Of the remaining 3% where there were differences between the field and laboratory methods, subsequent NIOSH evaluation attributed these differences to the variability (incomplete mixing, inadequate drying of the sample, the particle size of the rock dust and/or coal dust) of the samples being analyzed, the retained moisture in those samples, and the inherent ash in the coal.

In considering these results and comparing the CDEM field measurements to the LTA laboratory measurements, it is important to understand the fundamental distinctions between the two methods. The determination of TIC by the LTA method is not itself a direct measure of explosibility, but a surrogate that calculates a single parameter associated with full-scale experimental results. This method is not based on particle size and treats all particles equally regardless of the size. In contrast, the CDEM utilizes a different approach, using optical reflectance to determine the ratio of rock dust to coal dust in a mixture, with full-scale experiments on flame propagation having already demonstrated the effects of varying the coal dust particle sizes and incombustible concentrations on the explosible vs. nonexplosible dust mixtures. A final important distinction between the two methods is that the CDEM offers real-time measurements of the explosion propagation hazard within a coal mine entry, allowing for immediate identification and mitigation of the problem, while the results from the traditional LTA method are not known for days or weeks after a sample is collected, allowing for the deficiency in rock dust to continue.

The conclusions of this study strongly support the field use of the CDEM to measure the explosibility of coal and rock dust mixtures, to more effectively improve the onsite adequacy of rock dusting for explosion prevention. Mine operators could use the CDEM on a regular basis to ensure that their rock dusting practices are achieving inertization requirements and meeting the intent of 30 CFR 75.403. MSHA inspectors could use the CDEM as a tool to immediately identify onsite explosibility hazards and initiate corrective action. A critical issue to both the LTA and the CDEM analysis methods is that the results are dependent on representative samples being collected for analysis.

Introduction

Federal regulations require that rock dust (RD) be applied in all underground areas of a coal mine to mitigate the propagation of a coal dust (CD) explosion. Prior to September 2010, U.S. Federal law 30 CFR 75.403 mandated that the nation's coal mines maintain a total incombustible content (TIC) of at least 65% in nonreturn entries and at least 80% in the return airways.[6,7] The 65% TIC requirement was based on an average particle size termed "mine-size dust," which was based on an average of representative samples collected from mines in the 1920s. To determine compliance with the federal regulation, mine inspectors systematically collect dust samples from sections of underground coal mines and send the samples to the Mine Safety and Health Administration (MSHA) National Air and Dust Laboratory at Mt. Hope, WV, for analysis of incombustible content.

The TIC analysis is a gravimetric (mass) measurement of the incombustible content (IC) of a coal and rock dust mixture. Generally, the analysis is attained using a low temperature ashing (LTA) method [NIOSH 2010]. Due to the inherent time needed to collect the samples, ship the samples, and then test the samples, the Coal Dust Explosibility Meter (CDEM) was developed to allow for immediate determination of the explosible reactivity of a coal and rock dust mixture. The device was tested using experimental coal and rock dust mixtures and on band samples collected by MSHA inspectors from underground coal mines [Harris et al. 2008].

In 2009–10, the National Institute for Occupational Safety and Health (NIOSH) and MSHA conducted an extensive cooperative study to contrast explosibility assessment as determined by the CDEM with explosibility assessment results as determined by the laboratory gravimetric analysis of incombustible content. Further, the study was able to evaluate the feasibility for inspectors to use the CDEM within 10 of MSHA's bituminous coal districts. This report will discuss the study results, with emphasis on comparisons of the CDEM explosibility assessment with the traditional method for determining the TIC. CDEM operation and the use and application of the commercial CDEM will also be discussed. Importantly, the study results are presented in the context of the current standard requiring not less than 80% TIC in all areas of an underground coal mine.

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[6] In September 2010, MSHA published an emergency temporary standard (ETS) increasing the total incombustible requirement in intake airways to 80%. The final rule 2011–15247, requiring 80% TIC in intakes, was effective June 21, 2011. The current study was conducted prior to the ETS and subsequent final rule.

[7] Total incombustible content (TIC) includes measurements of the as-received moisture in the samples, the ash in the coal, and the rock dust. Incombustible content (IC) includes measurements of the ash in the coal and the rock dust and does not include the moisture.

Background on Coal Dust and Explosibility Testing

Coal dust particle size has a significant impact on the explosion propagation potential of coal and rock dust mixtures. As the coal dust particle size decreases, the coal particles are more reactive and increased amounts of compliant rock dust are necessary to render the coal dust inert.[8] Coal particle size has a high variability both within and between mines, with size being dependent on factors such as mine type (i.e., longwall or continuous miner), bit 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 further down the entries.

Numerous coal dust explosion tests have been conducted in the NIOSH Lake Lynn Experimental Mine (LLEM) to specifically quantify the concentration of rock dust required to prevent flame propagation [NIOSH 2010]. These tests studied flame propagation as a function of coal dust particle size while using a rock dust particle size of ~75% < 200 mesh (volume median rock dust particle diameter of ~ 25 microns, or µm) (Figure 1). Based on these results, the greatest impact on explosibility is evident between the particle size of the 20% < 200 mesh coal (mean coal particle diameter of 96 microns, µm) and 80% < 200 mesh (mean coal particle diameter of 33 µm). To ensure nonpropagation within the LLEM, the 20% < 200 mesh coal dust required a 70% TIC (~ 68% rock dust) and the 80% < 200 mesh coal required ~ 81.5% TIC (80% rock dust) to prevent sustained flame propagation. Once the 80% < 200 mesh benchmark had been reached, no additional incombustible content (IC) was required to prevent flame propagation with further decreases in coal dust particle size under these full-scale experimental conditions.

[8] Compliant rock dust is defined in 30 CFR 75.2 as "Pulverized limestone, dolomite, gypsum, anhydrite, shale, adobe, or other inert material, preferably light colored, 100 percent of which will pass through a sieve having 20 meshes per linear inch and 70 percent or more of which will pass through a sieve having 200 meshes per linear inch; the particles of which when wetted and dried will not cohere to form a cake which will not be dispersed into separate particles by a light blast of air; and which does not contain more than 5 percent combustible matter or more than a total of 4 percent free and combined silica (SiO_2), or, where the Secretary finds that such silica concentrations are not available, which does not contain more than 5 percent of free and combined silica."

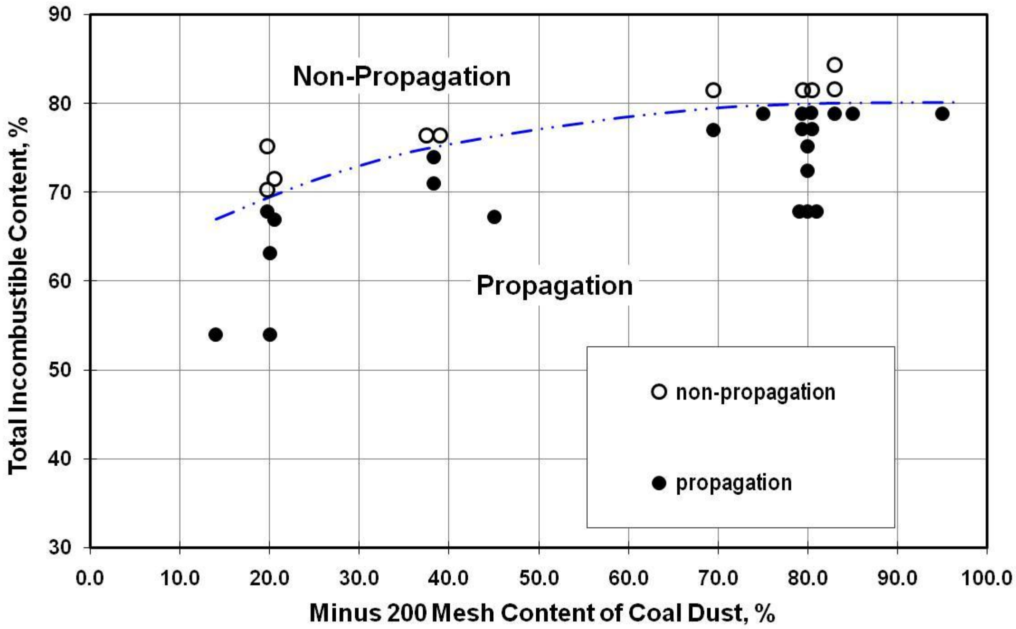

Figure 1. Effect of particle size of Pittsburgh seam bituminous coal dust on the explosion propagation for % TIC as tested within LLEM [NIOSH 2010]. The dashed curve represents the propagation/nonpropagation boundary.

To determine compliance with current regulations set forth in 30 CFR 75.403, inspectors from MSHA periodically collect samples of deposited dust from specified areas in a mine. The MSHA National Air and Dust Laboratory determines TIC and compares this TIC with the standard of 80% minimum TIC.[9] The TIC includes measurements of the moisture, the ash in the coal, and the rock dust. If 10% of the samples collected in a survey are < 80% TIC (in the absence of methane[10]), MSHA considers the sample survey to be noncompliant. The mine operator is issued a citation and a timeframe is stipulated to abate the citation. Abatement is accomplished by applying additional rock dust to the deficient areas from which the sample was collected. Abatement is confirmed through visual assessment by the MSHA inspector, but no followup dust samples of the abated area are collected or analyzed to ensure compliance with the respective intake or return airway TIC requirements.

[9] The 80% TIC requirement is based on explosion temperature thermodynamic limit models for coal and rock dust mixtures, extensive in-mine coal dust particle size surveys, and multiple explosion experiments at the Lake Lynn Experimental Mine [NIOSH 2010]. Presently, the size of the coal dust particles is not determined by the MSHA National Air and Dust Laboratory as part of the explosibility assessment.

[10] Per 30 CFR 75.403, "Where methane is present in any ventilating current, the percent of incombustible content of such combined dust shall be increased 0.4 percent for each 0.1 percent of methane."

CDEM Operation

The CDEM (Figure 2) is a handheld device developed to assess the explosibility of coal and rock dust mixtures in real time. The principle of operation of the device is based on the measurement of near-infrared radiation reflected from the surface of a homogeneous mixture of two dusts with different optical reflectance, in this case light-colored rock dust and dark coal dust. Near-infrared radiation is emitted by a light-emitting diode located behind the window of the CDEM probe.

When the CDEM probe is inserted in the dust mixture, the near-infrared radiation reflects off the surface of the dust and back to a silicon photodiode sensor. The normalized reflectance, Φ, is related to the rock dust to coal dust particle density ratio and the ratio of the mean particle diameters of coal to rock dust contained in the mixture. The normalized reflectance for the tested sample is compared to that of the calibration sample. If the test sample normalized reflectance is greater than that of the calibration sample, it is determined to be nonexplosible. If it is less than the calibration sample normalized reflectance, it is classified as explosible. For further detail on the CDEM design, calibration, and operation, see Appendices A, B, and C.

Figure 2. Coal Dust Explosibility Meter (CDEM).

Operationally, the CDEM uses a digital readout that identifies a sample as being either "RED" or "GREEN." For the prototype CDEM used in this study, the meter identifies a sample as RED (potentially explosible and requiring more rock dust) when the measured Φ is ~ 6% or more below the extinction limit Φ* needed to prevent flame propagation (Figure 1 and Figure A2).[11] The extinction limit Φ* is the boundary between propagation and nonpropagation and is set at the 80% rock dust level during CDEM calibration. The CDEM identifies a sample as GREEN (nonexplosible) when the measured Φ is equal to or greater than the extinction limit Φ*.[12]

Comparison of Laboratory Results and CDEM Results

The traditional low temperature ashing approach to determine if a coal and rock dust mixture passing through a 20 mesh sieve (< 850 µm) is compliant with the inert requirement is significantly different from that approach used by the CDEM for assessing the potential explosibility of the coal and rock dust mixture. The current LTA method actually consumes the coal dust and considers the remaining material to be inert. Compliance with the law is then determined by comparing the measured percentage of inert material of the representative band sample with the pre-established requirement of 80%. The TIC of the sample includes the rock dust, the amount of moisture as received at the lab, and the inherent ash in the coal. The LTA method is not itself a direct measure of explosibility but is a surrogate that calculates a single parameter associated with full-scale experimental results and is also insensitive to particle size. In contrast, the CDEM determines the potential reactivity of the coal and rock dust mixture by optically comparing the ratio of the surface area of the rock dust particles to the surface area of the coal dust particles, and relates the measured ratio to a stored 80% rock dust/coal dust calibration sample at the extinction limit of Φ*. The 80% calibration sample is prepared with the particular rock dust used at the coal mine and mixed with the standard Pittsburgh pulverized coal (PPC) dust [80% < 200 mesh (~ 74 µm)].[13]

When comparing methods that make accuracy determinations, the tendency is to compare the new method with the traditional method head-to-head. In this case, since the LTA method and the CDEM use different means to determine the explosibility of a coal and rock dust mixture, it is difficult to directly compare one method with the other. The only effective approach should be

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[11] The commercialized version of the CDEM identifies a sample as RED when the measured Φ is below the extinction limit Φ* needed to prevent flame propagation—i.e. when less than 80% rock dust.

[12] In addition to RED and GREEN, the prototype CDEM also identified a sample as YELLOW when the measured Φ was within 5% of the extinction limit Φ*. A YELLOW reading indicated that the sample was marginally explosible. This feature was eliminated as unnecessary in the later-developed commercial version of the CDEM. However, in this report, the YELLOW readings were considered to be RED in the analysis of the data discussed in this report. Although the YELLOW measurements are not discussed separately, all of the RED, YELLOW, and GREEN measurements are included in this report.

[13] Pittsburgh pulverized coal (PPC) has been used in large-scale explosion tests at the Lake Lynn Experimental Mine (LLEM) and is the standard upon which the 80% total incombustible content cited in 30 CFR 75.403 is based [NIOSH 2010].

outcomes-based, i.e., to compare the LTA prediction with the CDEM prediction and judge both against actual explosion tests conducted with samples using a laboratory test chamber [Cashdollar 1996, Cashdollar and Chatrathi 1993, Cashdollar and Hertzberg 1989, Cashdollar et al. 1987, Cashdollar et al. 1992a, 1992b, and 1992c, Lucci et al. 1995, Weiss et al. 1989]. The following sections detail how this approach was used for this report.

Joint Study between NIOSH and MSHA

A cooperative study between NIOSH and MSHA entailed an MSHA inspector from each of the 10 bituminous coal districts using the CDEM in mines to identify potentially explosible dust mixtures in real time during routine band sample surveys. The study was initiated with one training session held at the National Mine Health and Safety Academy in Beckley, WV (see Appendix B). The mine inspectors were to collect the band sample during their routine survey, measure the explosibility with the calibrated CDEM (per the methods described in Appendix C), and then send the mixed sample to the MSHA National Air and Dust Laboratory for the routine laboratory determination of the percentage of TIC (% TIC). The remainder of the samples would then be sent to NIOSH for parallel testing. The CDEM output obtained by the mine inspectors was shared with NIOSH researchers as well as the corresponding MSHA TIC for each sample.

After the in-mine band samples were collected by the inspectors, the samples were submitted to the MSHA National Air and Dust Laboratory for routine testing to determine % TIC per the MSHA standard sampling protocol and procedure. The MSHA inspectors were directed to record the CDEM readings in the “Location in Mine” column on their Rock Dust Sample Submission Forms.

The inspectors began using the CDEMs in December 2009 (within one month of receiving the training on the proper use of the CDEM). NIOSH requested the inspectors send pure rock dust samples from each mine sampled directly to the NIOSH Office of Mine Safety and Health Research (OMSHR) Pittsburgh location. Once the % TIC was determined, MSHA was asked to send NIOSH the remainder of the dust samples from the surveys in which a CDEM was used by the inspectors, along with the TIC analyses and moisture content data.

A brief look at the dust sample processing time involved in this study reveals a fundamental problem related to the traditional LTA method. Although the average dust sample processing time in this survey was less than 2 weeks, the total elapsed time from the sample collection date until the laboratory informed the MSHA inspector of the results ranged from 1.7 weeks to 5.9 weeks, with an average of 3.6 weeks (Table 1). This period does not include the time elapsed between receipt of the results by the inspector and notification to the mine. During this processing period, the mine entry where the band sample was taken could be deficient in rock dust, thereby representing a potentially unrecognized and unmitigated hazardous condition.