Large-scale Dust Explosions: Treated vs. Non-treated Rock Dust

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Introduction

One of the goals of the National Institute for Occupational Safety and Health (NIOSH) is to conduct research to reduce the risk of mine disasters and provide workplace solutions to reduce the risks associated with accumulations of combustible and explosible materials; the most common form of which is the generation of coal dust during the mining process and its subsequent distribution downwind. Dispersible rock dust is a primary defense for preventing coal dust explosion propagation in underground coal mines, and its properties are defined in 30 CFR 75.2. “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.”

An earlier NIOSH investigation of rock dust revealed two significant concerns with the supply of rock dust to U.S. coal mines: 1) insufficient particles <200 mesh (75 µm) and 2) all rock dusts when wetted and dried formed cakes and were not easily dispersed with a light blast of air [NIOSH 2011].

Past research by the U.S. Bureau of Mines and others showed that bituminous coal dust remains dry and dispersible in the presence of moisture [U.S. Bureau of Mines, 1962]. Rock dust must also be dispersible in concert with the coal dust to effectively inert a propagating coal dust explosion [Cybulski 1975; Michelis et al. 1987; Reed et al. 1989; Lebecki 1991]. Non-treated rock dust, however, readily absorbs moisture, limiting its dispersibility, while a rock dust treated with long-chain fatty acids (such as stearic acid) or other additives can remain dry and dispersible. Stearin-treated rock dust has been used in British coal mines [Powell and Taylor 1964] and is commonly used in Polish coal mines.

Traditionally, testing in large-scale explosion research facilities has been required to decisively demonstrate the effectiveness of rock dust and to provide supporting data for decision-making regarding explosion safety in underground coal mines. Due to closure of the Lake Lynn Experimental Mine, the Experimental Mine Barbara (EMB) of the Polish Central Mining Institute (CMI) was used as an alternate facility to compare the relative effectiveness of a treated rock dust to that of an similarly-sized non-treated rock dust under the same experimental test conditions. Fundamental research has been conducted in the EMB on a large-scale basis since 1925 to address the explosive danger of coal dust, firedamp and flammable fire gases [Cybulski, 1975]. Such research includes examining main explosion parameters, rock dust suppression effects, initiator effects, accumulations of fire damp, and barriers.

This report presents the results from laboratory and large-scale explosion experiments conducted at EMB to help answer the question “Will treated rock dust be as effective as non-treated rock dust in attenuating or quenching coal dust explosions under the same experimental test conditions?”

Test Method

Due to prohibitive shipping costs, the Reference rock dust and pulverized Pittsburgh coal (PPC) dust traditionally used in NIOSH large-scale testing were not used. The rock dusts used in the EMB tests were obtained from Labtar (Tarnów Opolski, Poland) which supplies treated and non-treated rock dusts to coal mines in Poland [Labtar 2018a, b]. The coal dusts used were a medium-sized dust, termed d38, for the propagation zone and a finer-sized dust, termed d96, for the ignition boost. Before conducting the large-scale tests, NIOSH verified the function of the dusts in the laboratory using the 20-L explosion chamber and compared the results to those obtained with the Reference rock dust which has historically been used in NIOSH laboratory and large-scale testing [NIOSH 2010].

To characterize the full particle size distributions, NIOSH used a Beckman Coulter (B-C) LS 13320 laser diffraction particle size analyzer equipped with a Tornado Dry Powder air dispersion system. NIOSH researchers followed the analysis procedure recommended by the manufacturer [Beckman Coulter, 2011; Harris et al., 2015; Perera et al., 2017].

The Polish d38 coal dust is a standard coal dust used at the EMB for dust explosion research. The B-C mass-mean diameter of the Polish d38 coal dust is 124.9 µm. Its particle size distribution is listed in Table 1.

Table 1. Particle size distribution of the Polish d38 coal dust.

Mesh Size	µm	B-C % <
635	20	6.2
400	38	13.6
200	75	33.6
60	250	91.6
20	850	100.0

The Reference rock dust has been used in full-scale explosion tests at Lake Lynn Experimental Mine for a number of years and is the rock dust used in the testing resulting in the 80% total incombustible requirement recommendation [NIOSH 2010]. Generally, the particle size distribution of the Reference rock dust has remained consistent. Table 2 shows the particle size distributions of the Reference rock dust and the Polish rock dusts as determined by the B-C instrument. The Reference rock dust has a mass-mean diameter of 72 µm. The Polish non-treated rock dust has a mass-mean diameter of 38 µm while the Polish treated rock dust has a mass-mean diameter of 28 µm.

Table 2 - Particle size distributions of Reference rock dust and the treated and non-treated Polish rock dust.

		Reference Rock Dust	Non-treated Polish Rock Dust	Treated Polish Rock Dust
		B-C	B-C	B-C
Mesh Size	µm,	% <	% <	% <
635	20	45.1	64.9	70.5
400	38	54.7	72.3	79.1
200	75	67.8	81.5	88.7
60	250	99.4	99.7	99.9
20	850	100.0	100.0	100.0

The dust explosibility experiments in this paper were conducted in the NIOSH 20-L explosion chamber [Cashdollar 1996, 2000; Going et al., 2000]. The ignition source was a 5000 J electrically activated pyrotechnic ignitor. A pressure rise > 1 bar (pressure ratio > 2) was used as the criterion for determining the occurrence of an explosion during a test. A pressure ratio designation can account for the variations in atmospheric pressure. This determination is in accordance with the ASTM test for measuring the explosibility of dust clouds (ASTM, 2010).

Table 3 lists the percentage of rock dust required to inert each of the d38 coal dust/rock dust mixtures in the NIOSH 20-L chamber. The percentage is also displayed for comparison since PPC has been used extensively in 20-L and large-scale testing [NIOSH 2010, Cashdollar 1996, 2000; Going et al., 2000; Harris et al., 2015]. There were explosions at the mixture ratio that was 5% less than those listed here. The data shows that both the treated and non-treated Polish rock dusts inert at the same percentage as the Reference rock dust. The differences in inerting percentages (75% for PPC vs. 60% for d38 Polish) are due to variations in particle size distributions, and ash contents for the two coal dusts.

Table 3 - NIOSH 20-L chamber test results. At each rock dust percentage, five tests were run with coal dust concentrations of 400 g/m^3 to determine the reactivity of the mixture. Tests were conducted with rock dust increments of 5%, and the final amount to inert was interpolated for values reported herein. For example, 73% of the Reference rock dust was required to inert PPC at a concentration of 400 g/m^3 used in this study.

Rock Dust	Coal Dust	% Rock Dust Inerting	Rock Dust	Coal Dust	% Rock Dust Inerting
Reference	d38 Polish	60	Reference	PPC	75
Polish non-treated	d38 Polish	60	Polish non-treated	PPC	75
Polish treated	d38 Polish	60	Polish treated	PPC	75

When examining the 20-L chamber test results shown in Table 3, there is no indication, based solely on these screening results, that one should expect to see a difference in relative effectiveness between mixtures of Polish treated and non-treated rock dust in attenuating dust explosions propagating in the EMB.

NIOSH used the EMB underground experimental facility to conduct large-scale propagating coal dust explosions. The facility consists of 200-m and 400-m experimental galleries equipped with datagathering systems and utilities to initiate dust explosions. An outline of the experimental gallery network is shown in Figure 1.

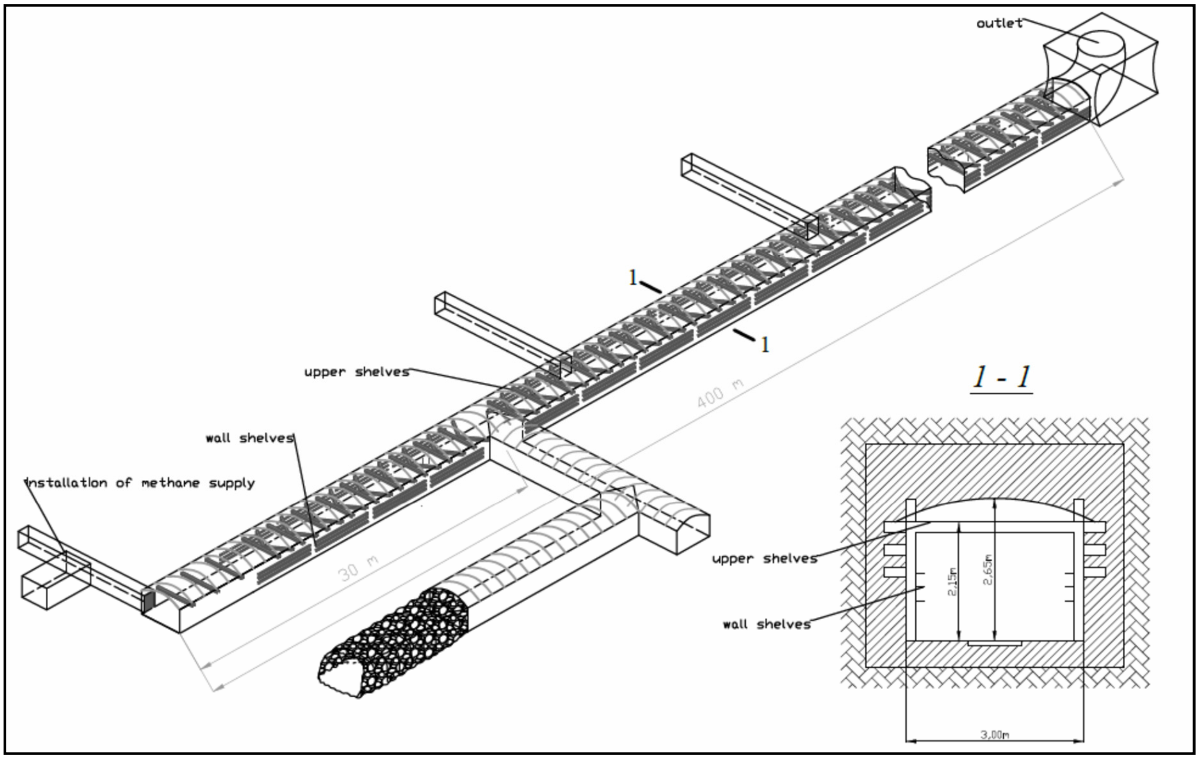

Figure 1. Layout of the 400-m long experimental gallery in the Experimental Mine Barbara, Poland.

These tests were carried out in the 400-m experimental gallery (7.5 m^2 cross section). This gallery is closed at one end and open to the atmosphere at the other. A gas supply and mixing chamber introduced 50 m^3 of a gas mixture containing 9.5% methane in air to the closed end of the gallery. A paper diaphragm was erected 6.7 m from the closed end to separate the gas zone from the rest of the gallery. Each propagation test began with ignition of the 50 m^3 gas zone using a 10 kJ chemical ignitor. Multiple ignition tests were conducted without any coal dust and rock dust to determine the reproducibility of the initial explosion pressures generated. The results showed the need to increase the strength of the ignition and subsequent propagation by adding 8.7 kg of fine d96 for a 3 m distance immediately outby the ignition zone (Figure 2).

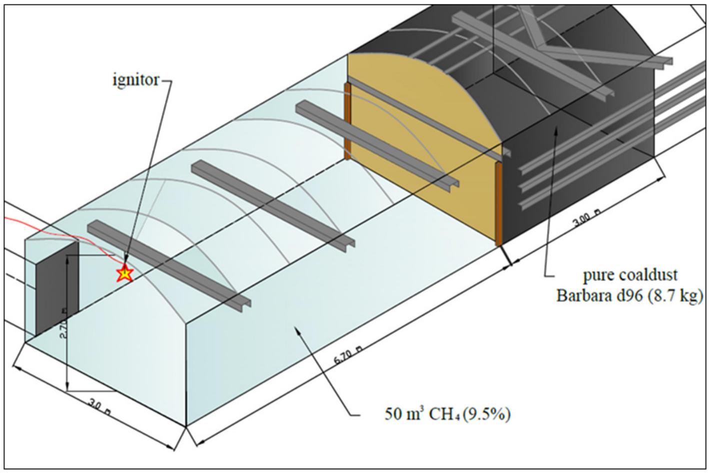

Figure 2 – Layout of the methane and coal dust ignitions.

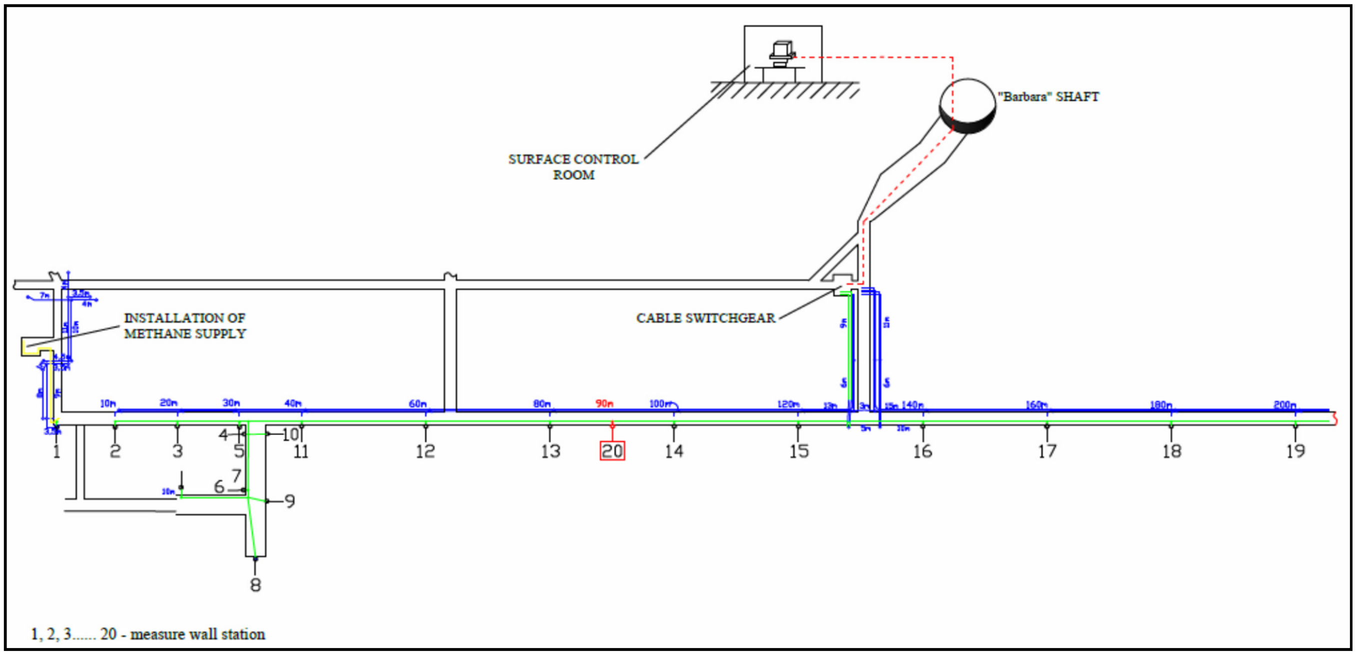

Figure 3. A Diagram of the registration system and the location of the measurement panels.

Measurement panels containing pressure transducers and flame sensors were positioned along the gallery walls (Figure 3). Data was collected at distances of 20 m, 30 m, 40 m, 60 m, 100 m, 120 m, 160 m, and 200 m from the end of the methane ignition zone.

The tests and conditions are listed in Table 4 for the treated rock dust (TRD) and non-treated rock dust (NTRD). All tests were conducted using a coal dust concentration of 220 g/m^3. The percentage total incombustible content (TIC) includes the water and ash content of the coal as well as the rock dust. Mixtures of coal dust and either treated or non-treated rock dust were distributed over a 100-m distance. Two-thirds of the 165 kg dust mixture was uniformly applied to the roof shelving while the remaining dust was applied to the wall shelves.

Table 4 – Test conditions at the Experimental Mine Barbara. The ignition coal boost is the addition of 8.7 kg of coal dust adjacent to the baffle for approximately 3 m.

Test	Rock Dust Type	% TIC	Ignition
1	TRD	60	methane
2	NTRD	60	methane
3	TRD	60	methane with d38 coal boost
4	TRD	50	methane with d96 coal boost
5	NTRD	50	methane with d96 coal boost
6	TRD	50	methane with d96 coal boost
7	NTRD	50	methane with d96 coal boost
8	TRD	50	methane with d96 coal boost
9	NTRD	50	methane with d96 coal boost
10	NTRD	60	methane
11	TRD	60	methane

Results and Discussion

As shown in Figure 4, the methane-only ignition tests have fairly good repeatability. A final methane-only test was conducted with the 3 m of fine d96 coal dust added immediately outby the methane zone. The pressure trace of this test was consistent with those of the first three methane-only tests. The cause of the observed offsets along the horizontal axis is not known but may be due to the path of the signal initiating the ignitor which runs over 100 m from the surface.

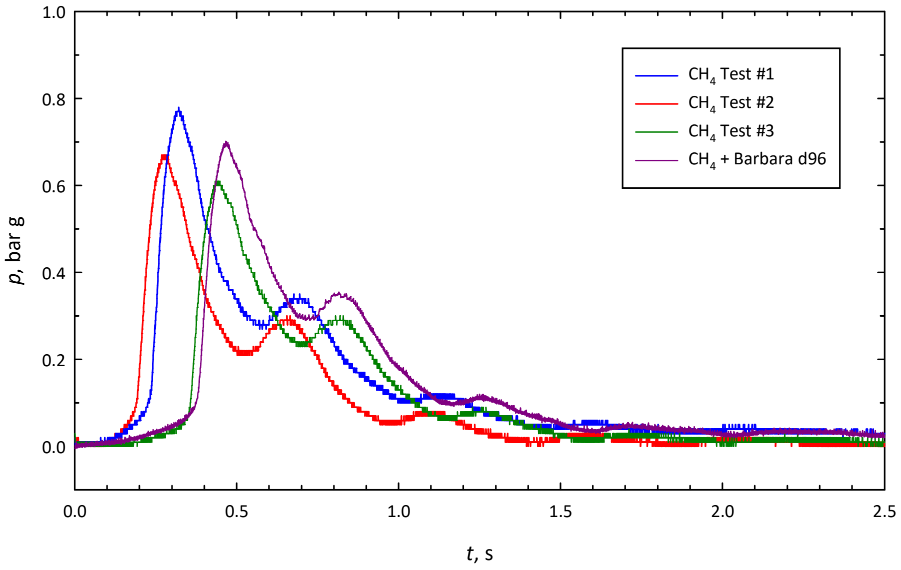

Figure 4 – Ignition pressure histories measured at 20 m.

Figure 5 displays the pressure histories at each measurement location for Test #3, 60% TRD. This typical example shows the advance of the explosion down the entry as each of the pressure peaks occur with the explosion losing strength with distance. The positive portion of the pressure curve (duration) shortens with distance when the reflected shock wave reverses the airflow.

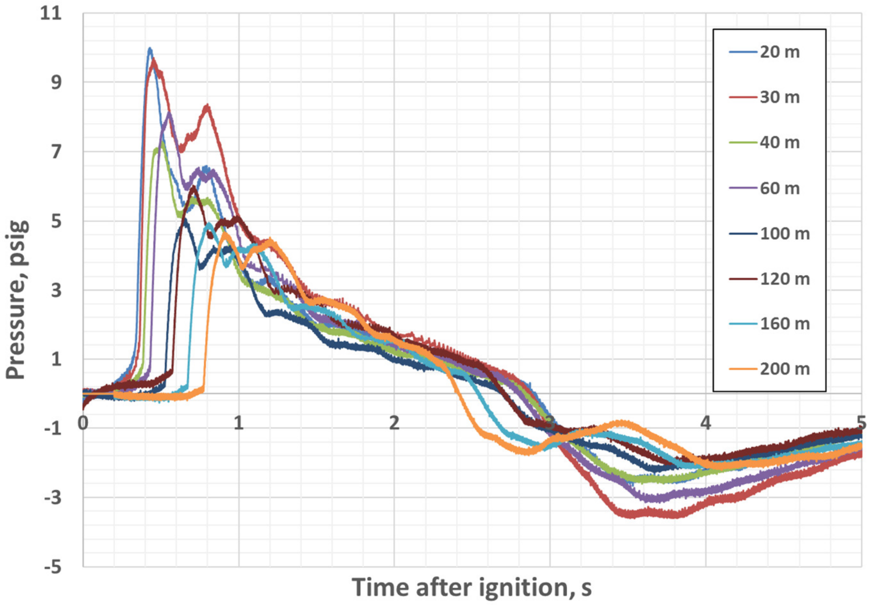

Figure 5 – A typical example of pressure histories at each measurement location. This is Test #3.

The strength of the explosion can be examined by considering the pressure impulses at each measurement location. The pressure impulse is the integral from the moment when the explosion pressure exceeds 10% of its maximum value until the time that the pressure drops below 0 bar g. In order to account for the varying ignition strength influences, the pressure impulse at each measurement location is normalized by the ignition pressure impulse. This scaled impulse is equal to the pressure impulse divided by the ignition pressure impulse. The ignition pressure impulse, $I_{p\ ig}$, is measured at 20 m, before the dusted zone and its influence, and is the positive integral of the curve until it reaches its first maximum pressure in the pressure history. See the inset of Figure 6 for an illustration of the ignition pressure impulse, $I_{p\ ig}$. By using this definition of ignition pressure impulse, the effects of the reflected pressure wave (and associated dust from the dust zone) are not included. The scaled pressure impulses at each measurement location are shown for each test in Figure 6.

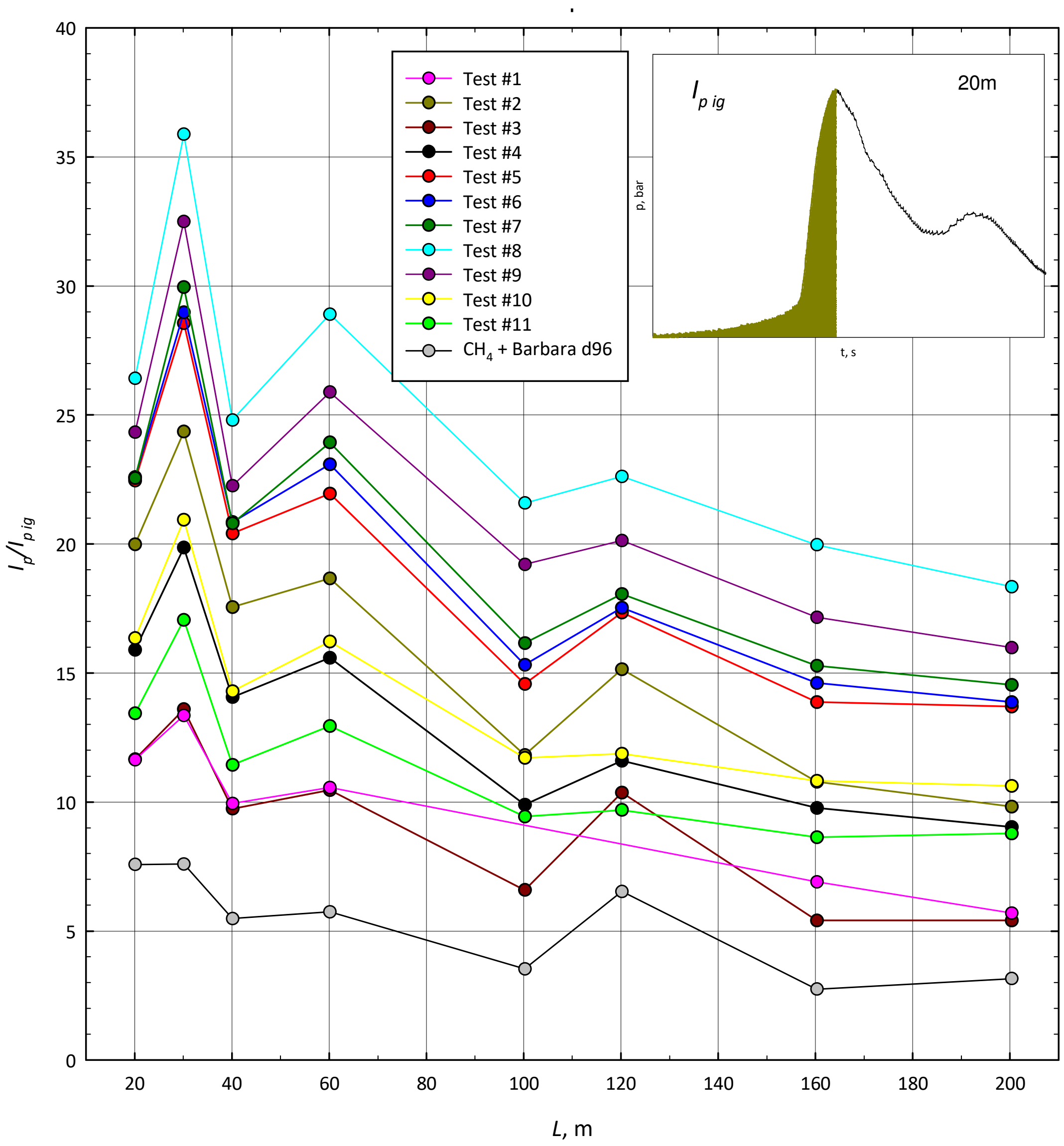

Figure 6 - Scaled pressure impulses for each test at each measurement location.

To compare inerting properties of TRD and NTRD dusts, average values of scaled impulses have been calculated for the similar mixtures of coal/rock dust (50 % and 60% total incombustible content or TIC). These data are listed in Table 5. The smaller average impulse indicates greater explosion intensity reduction. For example, at the 50% TIC concentration, the average explosion intensity for the treated rock dust (15.6) is slightly lower than that of the NTRD (16.7). At 60% TIC, the average explosion intensity of 7.7 for the TRD is lower than the average impulse of 11.8 for the NTRD. These averages also suggest that the performance of TRD increases with increasing rock dust percentage.

Table 5 - Listing of average impulses at 100 m when using 60% and 50% TIC of treated and non-treated rock dusts.

% TIC	Type of Rock Dust	Average Impulse at 100 m ($I_p/I_{p\,ig}$)
60%	TRD	7.7
60%	NTRD	11.8
50%	TRD	15.6
50%	NTRD	16.7

To further examine the consequence of rock dust treatment on inerting effectiveness, the average scaled pressure impulses were compared at each set of test conditions (% TIC, TRD vs. NTRD). Figure 7 shows this data where each data point represents the average scaled impulse at each of the 8 measurement locations along the test gallery (20, 30, 40, 60, 100, 120, 160, and 200 m outby the methane zone). This graph reveals that the 50% TRD mixture is slightly more effective at inerting than the 50% NTRD mixture; although the differences are likely not significant given the width of the standard deviation bars. If the treated and NTRD/coal dust mixtures had equivalent inerting effectiveness, the markers would fall along the black diagonal line. However, the NTRD scaled pressure impulses are consistently larger than the scaled pressure impulses for the TRD at the same measurement locations. In tests with a 60% %TIC, the data shows a greater inerting advantage with the TRD compared to the NTRD. This data implies improved inerting performance on behalf of the TRD at the higher concentration, especially considering that these tests were conducted in higher relative humidity, ranging from 75% – 92%.

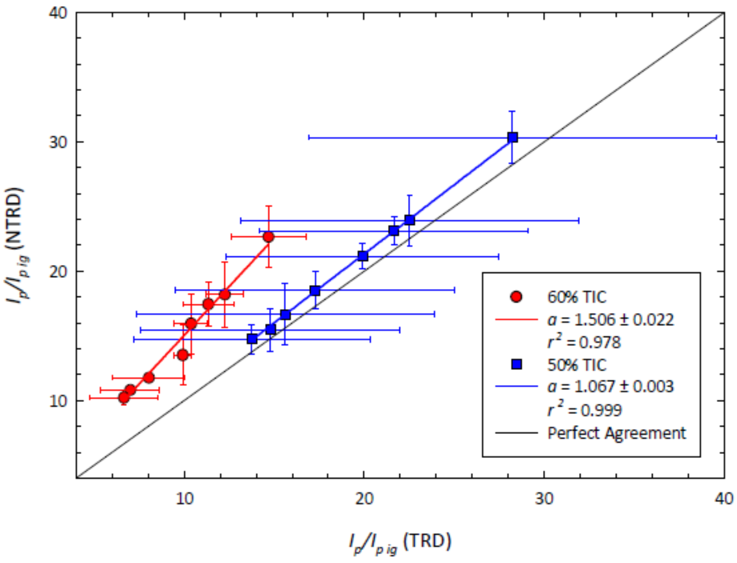

Figure 7 - A comparison of the scaled pressure impulses at each measurement location. Error bars represent standard deviations of the averages.

Based upon the results from this limited testing, the capability of a TRD to suppress a coal dust explosion is at least as good as that of a NTRD. For larger values of % TIC, the capability seems to be even better. Based on the preliminary laboratory tests conducted in the NIOSH 20-L chamber, there is no physical reason for uniform coal dust/TRD mixtures to be less explosible than those of coal dust/NTRD. The difference may be explained by the differences in dispersibility of the rock dusts; in that for similar tests, an explosion pressure wave may produce a cloud having a larger treated rock dust content than non-treated rock dust content, especially if the humidity in the gallery is high. It was observed that at high humidities, non-treated rock dust tended to agglomerate even during distribution of the dust mixtures on the ribs and shelves. Large agglomerates are difficult to entrain and the dust cloud formed during an explosion test would likely contain less rock dust than present in the initial mixture.

Conclusion

The National Institute for Occupational Safety and Health (NIOSH) conducts research to reduce the risk of mine disasters and provide workplace solutions to reduce the risks associated with accumulations of combustible and explosible materials. A series of large-scale tests were conducted at the Polish Experimental Mine Barbara (EMB) to compare the relative inerting effectiveness of a non-treated rock dust to that of a rock dust treated to resist moisture absorption. In general, the Polish rock dust samples reacted similarly as the Reference rock dust in the 20-L chamber. Since the goal was to assess differences in inerting effectiveness between treated and non-treated rock dust, this did not present an issue when conducting large-scale tests at the EMB. Tests using similarly-sized treated and non-treated rock dusts at the same conditions were conducted and the two sets of results compared on a relative basis.

The treated rock dust appeared to perform as well as the non-treated rock dust at a % TIC of 50%. At a % TIC value of 60%, the treated rock dust appeared to be even more effective since the scaled pressure impulses were smaller than those of the non-treated rock dust. Therefore, it would appear that the rock dust treated for anti-caking was, at least, as effective as the non-treated rock dust for attenuating a propagating coal dust explosion. The use of a treated rock dust is an available option to reduce the risks associated with accumulations of combustible and explosible materials.

This study was limited by the amount of testing that could be conducted at EMB given the financial constraints for this initial effort. Additional testing would have further confirmed differences in inerting effectiveness between the treated and non-treated rock dusts. Additionally, this study used homogenously-mixed samples of coal dust and rock dust. Although this testing was preliminary, questions remain on how layering of the coal and rock dusts could affect rock dust performance. Finally, these tests did not investigate the impacts of dust wetting on inerting performance. However, the high humidity levels measured underground did lead to observed agglomeration of non-treated rock dust particles, likely reducing the inerting ability of that rock dust.

Future Research Planned at CMI

Future efforts will continue in the fall of 2018 and into 2019 at the EMB. Since the practice of rock dusting in mines is often an intermittent process, this future effort will compare the relative effectiveness of treated and non-treated rock dusts when layered with float coal dust. The effects of moisture will be included in this work.

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