2016

MODERN ROCK DUST DEVELOPMENT AND EVALUATION FOR USE IN UNDERGROUND COAL MINES

Robert Eades
University of Kentucky, rqeades@gmail.com
Digital Object Identifier: http://dx.doi.org/10.13023/ETD.2016.034

STUDENT AGREEMENT:

I represent that my thesis or dissertation and abstract are my original work. Proper attribution has been given to all outside sources. I understand that I am solely responsible for obtaining any needed copyright permissions. I have obtained needed written permission statement(s) from the owner(s) of each third-party copyrighted matter to be included in my work, allowing electronic distribution (if such use is not permitted by the fair use doctrine) which will be submitted to UKnowledge as Additional File.

I hereby grant to The University of Kentucky and its agents the irrevocable, non-exclusive, and royalty-free license to archive and make accessible my work in whole or in part in all forms of media, now or hereafter known. I agree that the document mentioned above may be made available immediately for worldwide access unless an embargo applies.

I retain all other ownership rights to the copyright of my work. I also retain the right to use in future works (such as articles or books) all or part of my work. I understand that I am free to register the copyright to my work.

REVIEW, APPROVAL AND ACCEPTANCE

The document mentioned above has been reviewed and accepted by the student's advisor, on behalf of the advisory committee, and by the Director of Graduate Studies (DGS), on behalf of the program; we verify that this is the final, approved version of the student's thesis including all changes required by the advisory committee. The undersigned agree to abide by the statements above.

Robert Eades, Student

Dr. Kyle A. Perry, Major Professor

Dr. Braden T. Lusk, Director of Graduate Studies

MODERN ROCK DUST DEVELOPMENT AND EVALUATION FOR USE IN UNDERGROUND COAL MINES

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering in the College of Engineering at the University of Kentucky

By

Robert Quentin Eades

Lexington, Kentucky

Co-Directors: Dr. Kyle A. Perry, Assistant Professor of Mining Engineering
and Dr. Braden T. Lusk, Professor of Mining Engineering

Lexington, Kentucky

2015

ABSTRACT OF THESIS

MODERN ROCK DUST DEVELOPMENT AND EVALUATION FOR USE IN UNDERGROUND COAL MINES

Abstract

Following the promulgation of new permissible respirable dust standards by MSHA in 2014, new alternative rock dusts were created that combined the advantages of current industry applications while potentially reducing miner exposure to respirable dust. Research was performed to compare the explosion suppressing and ejection characteristics of three new types of rock dust to existing rock dust types. Explosion suppression tests were conducted in a 38-L chamber where pressures were recorded. Angle of ejection tests were conducted using a high explosive shock tube and high speed photography to determine angle of ejection and lift velocity. A comprehensive comparison of the results of these tests shows that these newly developed dusts have improved results for flame suppression and ejection when compared to typical wet dust applications.

KEYWORDS: coal mining, mine safety, respirable dust, rock dusting, flammability testing

Robert Eades

10/29/2015

MODERN ROCK DUST DEVELOPMENT AND EVALUATION FOR USE IN UNDERGROUND COAL MINES

By

Robert Quentin Eades

Kyle Perry

Co-Director of Thesis

Braden Lusk

Co-Director of Thesis

Braden Lusk

Director of Graduate Studies

ACKNOWLEDGMENTS

The author would like to thank:

Dr. Kyle Perry, graduate advisor and professor of Mining Engineering at the University of Kentucky, for his advice, support, and creation of an environment that allows students to succeed.

Dr. Braden Lusk, professor of Mining Engineering at the University of Kentucky, for his support, both in conducting my research and in participating as a member of my committee.

Kevin Harris, Ph.D. candidate at the University of Kentucky, and Michael Raffaldi, for their technical insights and encouragement during my research.

My fellow graduate students who helped me perform construction and conduct testing during my research. Josh Hoffman, Josh Calnan, Qingqing Huang, James Samples.

Ed Thompson, laboratory supervisor for the department of Mining Engineering at the University of Kentucky, for his encouragement, and knowledge about life.

The members of my committee – Dr. Kyle Perry, Dr. Braden Lusk, and Dr. Chad Wedding, for their participation and feedback.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

1.1 General Background

The Mine Health and Safety Administration (MSHA) classifies any mining accident that claims five or more lives as a mining disaster [MSHA Factsheet, 2015]. Explosions in underground coal mines are among the most notable and deadly classification of mining disasters. Before the creation of the Bureau of Mines (BoM) in 1910, 120 mining disasters were recorded in the coal mining industry. The two deadliest coal mine disasters were caused by explosions resulting in a combined total of 625 fatalities. Explosions have decreased through decades of research and implementation of new technologies and preventative programs [MSHA Factsheet, 2015]. However, when explosions do occur, they still have the potential to be classified as a mining disaster. Twenty-one (21) mining disasters have been recorded since 1970 which have resulted in 262 fatalities. Among these disasters, fifteen (15) were classified as an explosion resulting in 201 fatalities. This accounts for 71% of all disasters and 77% of all fatalities from disasters. Prevention and mitigation of coal mine explosions is widely researched, beginning shortly after the creation of the Bureau of Mines in 1910. There are several methods of mitigating the effects of a coal mine explosion. One of the most common methods is the use of a practice called “rock-dusting.”

Rock dusting is the practice of applying pulverized, inert rock (primarily limestone) to the roof, ribs, and floor of all areas of the mine. Rock dusting standards have been in place since the American Engineering Standards Committee (AESC) issued the first technical specifications for rock dust used in underground coal mines [Rice et al. 1930]. These specifications have been redefined a few times throughout the 20th century. With each of these specifications, the size requirement for the rock dust has become increasingly finer. The current definition of rock dust states that 100 percent of the material must be able to pass through a sieve having 20 meshes per linear inch (#20 sieve) and 70 percent or more passing through a sieve having 200 meshes per linear inch (#200 sieve) [Title 30 CFR section 75.2]. It is important to note that in the current definition of rock dust there is no minimum particle size that must be used. This trend towards finer particle sizes can lead to issues with respirable dust. Previous research has shown that during dry dusting, if the rock dust does not properly adhere to the surfaces of the entry, the particles can be carried by the ventilation air current to the face where the active mining is occurring [Hartmann and Westfield, 1956].

As of August 1, 2014, MSHA has issued a final rule that will change the permissible levels of respirable dust for all underground miners, and includes revisions for sampling methods to determine if mines are in violation of the new permissible levels. This raises concerns that applying dry rock dust will cause the mine to be in violation of the new levels. The application of dry rock dust is the most commonly employed method of rock dusting in the U.S. This method of rock dusting consists of direct application of the rock dust, with no modification, to the surfaces of the entry. This can be done either by hand or through the use of a hydraulic pump. However, a noted concern with dry dusting is increased respirable dust levels. An alternative method of rock dusting involves creating a water slurry with the rock dust, however, research has shown that this can decrease the ability of the rock dust to suppress an explosion, [Hartmann and Westfield 1956].This reduction in the ability to suppress an explosion is caused by caking. This phenomenon is explained further in section 2.4 of this thesis. Alternative methods of rock dusting have been created that combine the benefits of the two traditional application methods, while reducing the negative effects associated with each of these methods.

1.2 Scope of Work

The objective of this work was to compare the flame extinguishing capabilities of five types of rock dust. These are: (1) traditional dry dust, (2) traditional wet dust, (3) hydrophobic dust, (4) Strata FoamDust, and (5) DSI DYWI dust. The approach is to use comparative analysis of the results of experimentation, rather than a ranking analysis of the various dust types based upon performance. This allows the mine management and engineers to determine the appropriate method/material suitable for their particular conditions. Rock dusting is dependent upon the unique conditions present at each mining operation, and therefore, a specific type of rock dust cannot be considered the “best”. The experiments performed in this research serve as a tool to show that the newly developed rock dust types have similar or improved performance to traditional dry or wet dust.

In the first section of this work, samples of the five dusts are created and placed in a steel explosive chamber. A predetermined weight of coal dust is placed on top of the rock dust within the chamber, along with a 5kJ igniter. The sample is dispersed within the chamber via a pulse of breathable air and then ignited. A pressure sensor is located in the chamber and the explosive pressure is recorded as a function of time through the use of computer software. This test allows for comparative analysis of the rock dusts' capabilities to suppress the simulated flame front of a coal dust explosion before significant propagation has occurred. The criteria for significant propagation have previously been established by the National Institute of Occupation Safety and Health through a similarly designed explosive chamber experiment [Cashdollar and Hertzberg, 1989].

Next, samples of the five dusts are placed at the end of a shock tube. A C4 charge is placed within the shock tube and detonated. The subsequent shockwave of the detonation is measured using free field pressure sensors, and the angle of ejection and lift velocity of the rock dust sample is calculated through the use of a high speed camera and a velocity screen with 1 ft. intersections. No criteria have previously been established for this experiment, and the data recorded from this are used strictly for a comparison of how each dust performs under the same conditions.

Finally, some general conclusions are made in regards to how each dust type performed, both in the individual tests and as a whole. The limitations of this research are discussed and suggestions for future research in the area of chemical optimization and long term analysis of the tested characteristics tested in this research are presented.

1.3 Organization of Work

Chapter 2.0 presents the literature and background information concerning the history of rock dusting in the U.S., the changes to the technical specifications that have occurred throughout the 20th century, the establishment of significant flame propagation criteria, and the recent promulgation of the final rule that causes concern for the current status of rock dusting. Chapter 3.0 discusses the method of sample preparation and the experimental setup for the flame suppression experiments. In Chapter 4.0, the results of the flame extinguishing experiment are presented and analysis of the results is given, and how they compare to the criteria for significant flame propagation. Chapter 5.0 presents the experimental setup for the angle of ejection experiments. Chapter 6.0 discusses the results of the angle of ejection experiments and an analysis of the performance of each dust type is discussed. Chapter 7.0 provides a brief cost analysis for two of the three newly developed rock dusts. Lastly, in chapter 8.0, conclusions and suggestions for future research efforts are presented.

CHAPTER 2 LITERATURE REVIEW

2.1 Rock Dusting

Rock dusting is a safety procedure primarily used in underground coal operations to mitigate the propagation of a coal dust explosion. The rock dust is applied to all exposed surfaces of each entry and crosscut in the mine. The dust will settle on these surfaces and serve two purposes. The first purpose is to prevent the underlying coal dust from being released into the entry following an explosive shockwave. Secondly, the rock dust will disperse into the entries and crosscuts and raise the incombustible content to act as a heat sink for the combustion reaction, which will prevent propagation of the explosion energy. This procedure can be performed using two methods: (1) application of the dust by hand, or (2) use of hydraulic machinery.

Figure 2.1 Rock Dust Machine Example [Pinkley et al. 2012]

Rock dusting serves as the primary safety operation for coal dust explosion suppression in underground coal operations. The dust used for these operations consists of pulverized limestone, dolomite, gypsum, anhydrite, shale, and/or adobe having less than five percent combustible matter or no more than four percent free or combined silica. If these silica concentrations are not available, a substitute standard of five percent free or combined silica is used [Title 30 CFR section 75.2]. Rock dust must be applied to all entries and crosscuts of the active sections of a mine to within 40 feet of active mining, unless the coal dust in the area is too wet or too high in in-situ incombustible material to propagate an explosion [Title 30 CFR section 75.402].

2.2 Historical Rock Dusting

Prior to the establishment of the BoM, several organizations cited the need for a bureau within the federal government that would collect, evaluate, and distribute valuable data to the mineral and mining industries. These calls were not acted upon until a series of disasters focused public attention on the loss of life in underground coal mines. The worst of these disasters was the explosion of the Monongah 6 and 8 mines in Monongah, West Virginia in 1907. This single disaster caused a total of 362 fatalities [NIOSH 2006]. The Organic Act of 1910 established the BoM and transferred the scientific investigations that had previously been conducted by the United States Geologic Survey (USGS). The initial research focus of the BoM was the identification of chemical and physical characteristics that allowed explosives to perform without starting a fire or explosion [NIOSH 2006].

To accomplish this task, the first step was to identify the cause of the previous explosions. Prior to the research following the series of disasters of the 1900s, fire damp, a generalized term for flammable gases in coal mines, was considered the primary cause and source of propagation of explosions, however it was noted that in all cases there was a significant amount of coked coal dust present throughout the mine following the explosions [Rice et al. 1911]. During this time, the Mining Association of Great Britain was conducting a study on the effects of stone-dust zones on preventing or limiting the explosion of a mixture of coal dust and air. Preliminary tests had previously been conducted in the same testing facilities with uninhibited coal dust explosions. These tests took place in a testing gallery at the Altofts colliery in Yorkshire.

Figure 2.2 Altofts Experimental Gallery After Explosion of Dust Occupying 450 Linear Feet of Gallery, August 11, 1908 [Rice et al. 1911].

In total, the gallery had a length of over 900 feet with a circular cross-section. The intake end was approximately 400 feet in length, and the return was approximately 295 feet in length. These tests used varying amounts of coal dust. Stone dust zones were placed in two locations for three tests: (1) on the return side of the coal-dust charge, (2) on the intake side of the coal-dust charge, and (3) on both intake and return sides of the coal-dust charge. The results of these tests showed that a coal dust explosion was extinguished after penetrating 22 to 125 feet into the stone dust zone; the distance was dependent upon the application method of the stone dust [Rice et al. 1911]. Based upon these results, two methodologies were developed to inert coal dust to prevent the propagation of an explosion. These were referred to as the “wet” methods and the “dry” methods [Rice, Jones 1915].

The fundamental difference between these two methods was the process by which the coal dust was made inert. The wet methods were designed to wet the coal dust to the point where it was inert. Dry methods were designed to release nonflammable dust into the atmosphere. This dust could then be used as a heat sink for the combustion reaction and eventually extinguish an explosion due to lack of sufficient energy [Rice, Jones 1915]. The former method was preferred in the U.S. because of the sufficient amount of available water, and the belief that rock dusting was insufficient alone to suppress an explosion. However, Great Britain and France widely adopted the latter method because of the results of the Altofts experiments, and difficulties implementing a large-scale mine water system. Although the dry method was not widely used in the U.S., the BoM released the first specifications for incombustible content in the mine atmosphere. It was found that dry mixtures containing 80 percent roof shale or 75 percent of either limestone dust or shale dust nearly free from combustible matter could prevent a violent explosion. A larger proportion of roof shale dust was required because it contains a higher percentage of combustible matter. [Rice, Jones 1915].

The first tentative technical specifications for rock dusting of underground coal mines were announced in 1924. By this time, rock dusting had become a widely accepted and commonly practiced safety operation. These specifications were concerned with the combustible matter, silica content, and the size distribution of these dusts. The first experiments concerning particle size for rock dust considered two different size specifications. The first was a "pulverized" dust in which at least 95 percent of the material passed through a 200 mesh sieve. The second material was coarser with only 27 percent of the material passing through a 200 mesh sieve. A series of experiments showed no more than five percent additional rock dust was required for the coarse material to behave identically to the finer dust material. However, the BoM was concerned with amount of free silica that miners were exposed to, and also issued specifications stating that rock dust should contain no more than 25 percent free silica. The coarse rock dust failed to meet this requirement in all experiments, and was therefore not acceptable for use in coal mines [Rice, Greenwald 1929].

It was also shown that if a rock dust with a small amount of fines is to be used, there should be a larger overall quantity of rock dust used [Rice et al 1922]. This will ensure that the amount of fine rock dust is greater than the explosibility limit of the particular coal dust. However, a rock dust that is slightly coarser than 100 or 200 mesh is preferred because of the tendency of these very fine particles to stick to the mine passages due to the inter-molecular forces acting on them. Shale was the initial rock dust of choice because of the ease with which it could be obtained. Shale was proven to be a suitable rock dust, and could be taken from roof shale layers if the combustible content was between five and ten percent [Rice et al. 1922]. However, in the U.S., finding a roof shale layer that contains less than ten percent of combustible matter proved to be difficult, and by the late 1920s, limestone had become the primary rock for use in coal mine rock-dusting [Rice, Greenwald 1929].

The 1930s marked the first experiments to implement changes to rock dust specifications. Official rock dusting practices in U.S coal mines were adopted by the AESC in 1925. After the adoption of rock-dusting U.S coal mines in 1924, the exact size specifications became a concern. The first size specifications for rock dust set by the BoM states that "the rock dust shall be ground until 50 percent will pass through a 200 mesh sieve, although smaller sizes maybe used provided that at least 30 percent passes a 200 mesh sieve, and it is proportionately larger than the amount of coal dust," [Rice et al. 1930]. The standards committee also specified that the air-dust mixture should contain at least 55 percent incombustible matter, and when in the presence of the methane, this mixture should be increased by ten percent for each one percent rise in methane concentration [Forbes 1939].

As different companies implemented different operating procedures for rock-dusting the BoM began to gather statistics about how these trends affected the dust's inherent ability to stop an explosion, the effects of atmospheric humidity on a layer of rock dust, and also on the prospect of caking of the rock dust [Greenwald 1938]. The results of Greenwald's research show that the moisture content of the dust always tends to be in equilibrium with the humidity conditions of the contact air. However, this changes when the rock dust is brought into contact with a wet surface or when moisture is directly deposited on the rock dust. The nature of rock dust tends towards agglomeration, while the difficulty of truly wetting coal dust is well known [Greenwald 1938]. He continues by stating that "a thick layer of coal dust so deposited is likely to remain dry and readily dispersible, whereas it is not possible to form a cloud of rock dust." With the advent of world war, there were no major advancements in the field of rock dust application in underground coal mines. However, the 1950s saw renewed interest in this subject, particularly with the concept of effective rock dusting and common misconceptions related to rock dusting practices.

Effective rock dusting is defined as the uniform and continuous application to the rib, roof, and floor of coal mine entries and cross cuts. The rate of application must be adequate to increase the incombustible content of mine dust to the new minimum of 65 percent. [Hartmann and Westfield, 1956]. The BoM also advised that rock dusting be carried as close to the active face as possible, and suggested to within at least 40 feet, which became the standard used by the Code of Federal Regulations.

The next major revision to the technical specifications for rock dusting came from the Coal Mine and Safety Act of 1969. This law increased the amount of incombustible content that was required for return ventilation airways. The BoM had previously recommended 65 percent in all airways. The new law increased the minimum incombustible content of return airways to 80 percent. This change was made in response to the concern of the higher amount of methane and coal dust that would be carried away from the face during mining. Previous research has shown that rock dust zones that are located on the return side of the explosion have increased difficulty in suppressing an explosion [Rice et al. 1911], and therefore a higher concentration of incombustible matter is required to ensure suppression. Two criteria were established to measure the performance of rock dust. These criteria set the standards for significant flame propagation.

Significant flame propagation is defined as the minimum propagation required to cause serious damage to personnel and equipment in the mine [Cashdollar, Hertzberg 1989]. The testing conducted to set these criteria is covered in a later section of this document. The two criteria are related to the explosive pressure that is achieved in a simulated coal dust explosion. These two criteria are as follows: (1) The pressure ratio be greater than 200 kPa (2 bar), and (2) The cubic root of the volume-normalized pressure time derivative be greater than 150 kPa m s^{-1} (1.5 bar m s^{-1}) [Cashdollar, Hertberg 1989]. Pressure ratio is defined as the maximum explosive pressure achieved divided by the pressure at ignition of the explosion. These two criteria can be used to evaluate the flame suppressing capabilities of various configurations, amounts, and incombustible matter concentrations of rock dust.

After the closure of the BoM in 1995, much of the research towards rock dusting and propagation prevention was turned over to the National Institute of Occupational Safety and Health (NIOSH). The research conducted after the closure of the BoM has primarily focused on the changing mean coal dust particle size. Until 2010, the requirements of rock dusting specifications were based upon particle size distribution analyses that had been conducted in the 1920s [Sapko et al 2007; Cashdollar et al 2010]. Earlier research had demonstrated that the inerting requirement for a given coal particle size decreases as the mean diameter of the rock dust decreases. This is because of the corresponding increase in surface area of the rock dust. However, altering the particle size of the coals has a dramatic effect on the inerting requirements. A small decrease in mean particle size of coal dust results in a substantial increase in the amount of limestone that is required to inert the mixture [Amyotte et al. 1995].

The most recent alteration to the technical specifications for rock dust were issued in 2010, the minimum requirements for incombustible content were changed such that the minimum incombustible content in both intake and return airways is 80% [NIOSH 2010]. This was done after the research team had conducted a series of particle size analysis distributions across the mining districts of the U.S. The conclusions of this research indicate that as mining has become increasingly mechanized, and as a result of increasing production and machinery with higher power, the coal dust particle size in intake airways is finer than measured particle sizes of the 1920s [NIOSH 2010].

2.3 Alternative Application Methods of Rock Dust

Originally, rock dust was applied by hand. The miners would periodically halt production and apply the dust from large bags. This method of dusting is still implemented today but can lead to inefficient and inconsistent application of the rock dust to various locations. Several methods for applying rock dust to the entries and crosscuts of a mine have been tested in the U.S. since becoming a popular safety operation. These methods were met with varying degrees of experimental and commercial success. They are primarily focused on the thorough and comprehensive application while requiring minimal production delays. The first alternative method that was tested in the early 1920s was the concept of discrete rock dust barriers that were erected at regular intervals. This was perceived as both a cheaper and more efficient method of suppressing an explosion than continuous dusting of the entry and cross cuts.

Seven tests were conducted at the BoM experimental mine that assessed the flame suppressing capabilities of rock dust barriers [Rice et al. 1922]. In these tests, the barriers were erected 300 feet outby the face. Five of these tests used barriers that were composed of 500 linear feet of roof shale material with an average incombustible content of 91.5 percent. In each of these tests, 1,500 pounds of shale dust was used. Two additional tests were conducted that used limestone dust that was transported from an off-site location. These barriers consisted of 100 percent incombustible material with a total linear length of 600 feet. These tests used a total of 3,000 pounds of limestone dust. In each of the experimental trials, a 300 foot coal dust zone was created inby the rock dust barrier leading to the face of the mine. The igniting shot was fire from a cannon at the face.

The results of these tests indicated that in all of the tests, the rock dust zone was able to successfully stop the explosion. However, a noted concern of the researchers was that these zones would become contaminated by coal dust, and that they could not reliably stop an explosion along the entire length of the barrier and that continuous dusting along the entire length of the entry would produce the most consistent results [Rice et al. 1922]. A follow-up study was conducted at the experimental mine using Taffanel barriers. These barriers were first developed by M. Taffanel in France. These barriers consisted of ten shelves that were 20 inches wide, placed transverse in all entries just under the roof on a center-to-center spacing of six feet.

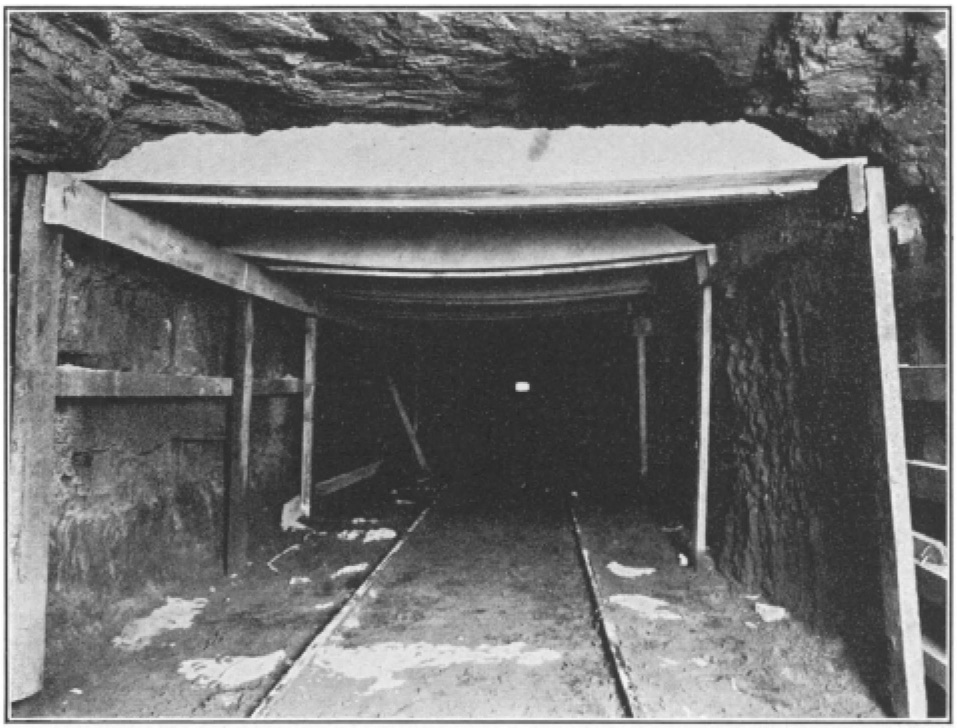

Figure 2.3 Taffanel Barrier Shelves Installed in Experimental Mine [Rice et al. 1922].

A total of 135 tests were conducted that involved a total of 207 barriers. Among these tests, 123 tests were conducted using a roof shale material and the remaining were conducted using an off-site limestone. 173 barriers were able to successfully stop the flame, 15 were considered failures, 4 had questionable results with no clear test result, and 15 barriers were the flame did not reach [Rice et al. 1922]. Initial tests used 10 Taffanel barrier shelves, however, over the course of the testing this number was increased to 15. Each shelf had an average capacity of 4 cubic feet and an average rock dust weight of 300 pounds. The results of this test proved that the Taffanel barriers were able to repeatedly suppress an explosion, however, there were two noted issues related to the use of these barriers.

The first issue noticed by the investigators was the failure of the barrier to operate in a low pressure explosion because the air movement would not blow enough dust off the barrier to suppress the flame. This indicated that the Taffanel barriers would have questionable performance if located too close in proximity to the ignition location, where the explosive pressure may not have fully developed. The second issue associated with these barriers had significant implication for U.S mines. Taffanel barriers placed in intake airways could cause the rock dust to become damp at certain points of the year [Rice et al. 1922]. This damp dust would then not readily disperse into the entry because of the agglomeration of the dust. This was of more concern to U.S. mines because the shallower mining depths are more affected by seasonal weather changes than the deeper European mines. To rectify this second issue, the BoM created several variations of the Taffanel barrier to be more sensitive to a low pressure explosion. The most extensively tested was called the box barrier.

Four types of box barriers were created and tested by the bureau between 1914-1915. These boxes were designated: box A, box B-1, box B-2, and box C. The fundamental concept of the design for these boxes was the same. These boxes were totally enclosed to prevent contact of the rock dust from moist ventilation air, thereby allowing the dust to disperse following a low pressure shockwave. These boxes have variations in how the barrier is installed and how the dust is dispersed. All box barriers had approximate dimensions of 8 feet long by 10 inches high by 22 inches wide [Rice et al. 1922]. Box A used suspension bars with hooks that were connected to the underside of the box. When the explosive shockwave passed by the box the hooks would be moved causing the contents of the box to be dumped into the entry. Twenty- three tests were conducted with the box A configuration, and seven of the trials failed to suppress the explosion. In these trials, the failure was caused by variations in the speed by which the explosive flame front followed the initial shockwave. In some trials the content of the box had already been dispersed into the entry before the flame front had arrived, and conversely, in other trials the flame front had already traveled beyond the box before the content was dispersed [Rice et al. 1922].

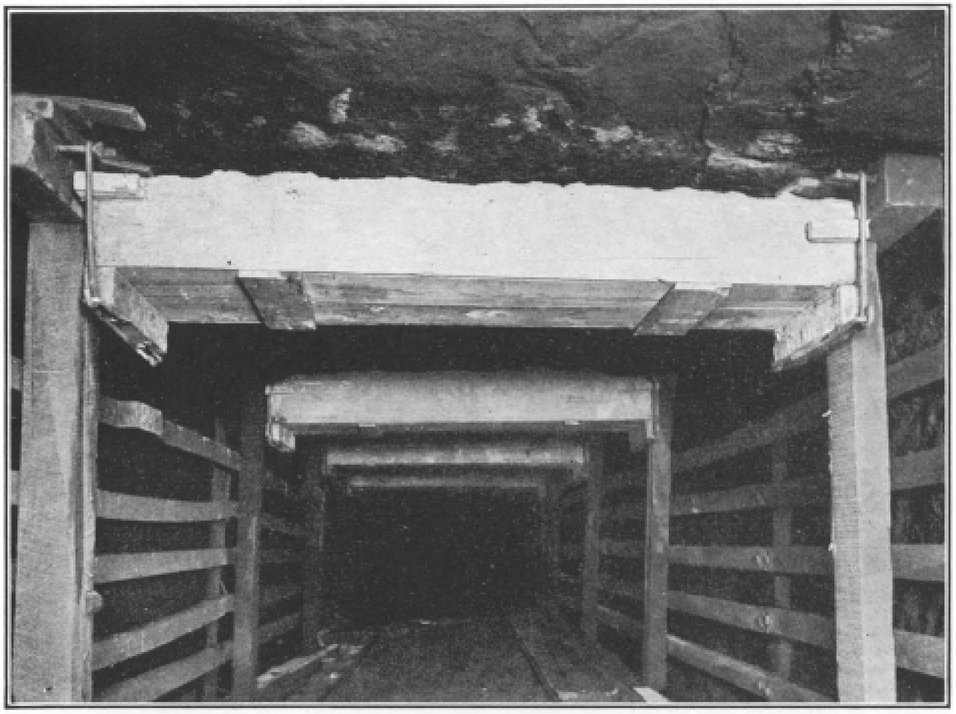

Figure 2.4 Box Barrier Type A Installed in Experimental Mine [Rice et al. 1922].

Boxes B-1 and B-2 were modifications made to the original box A design; the primary difference between these designs was the underside of the box was not rigidly connected to the balance of the board. Chains were attached to the hooks on the underside of the box which served two purposes. The first is that the dust contents are further broken up as it is dispersed into the entry which prevents the rock dust from being dumped as a concentrated heap instead of covering a larger surface area in the entry. The second is that the entire content of the box could not be dispersed immediately as a portion of the dust was still supported by the area directly above the suspended chains [Rice et al. 1922]. When the flame front of the explosion arrived at the box barrier the remainder of the retained dust would then be blown into the entry and quenches the flame. Seventeen (17) trials were conducted using the B-1 configuration, and of these the flame was able to reach the box barrier in twelve (12) trials. Of these twelve (12) trials, the box was able to successfully suppress the flame front in ten (10) trials. Thirty-nine (39) trials were conducted using the B-2 design. In twenty-two (22) cases the flame front of the explosion was able to reach the box barrier, and there seven (7) failures were recorded. However, it is important to note that in seventeen (17) of the trials in which the flame front did not reach the barrier, the contents of one or more of the boxes was still dumped into the entry [Rice et al. 1922].

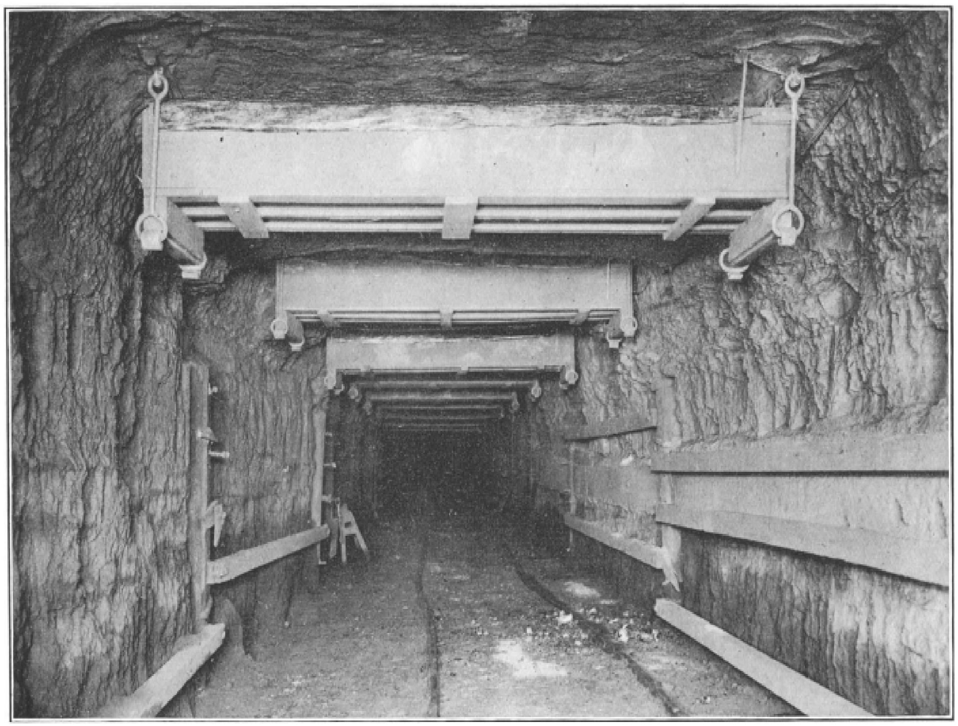

Figure 2.5 Barrier of Six B-2 Boxes in Mine Entry. Rock Dust is Protected by Oilcloth Covers [Rice et al. 1922].

The type C box barrier utilized two grids that were placed above the bottom boards of the box and were also suspended by the chains when the barrier was operational. These grids exposed a greater dust surface to the air current which allowed for more rapid dispersion of the dust into the entry. Fifty-four (54) tests were conducted using the type C design. Thirty-five (35) tests were recorded where the flame front was able to successfully reach the box barrier, and among these trials, twenty-five (25) were considered a success.

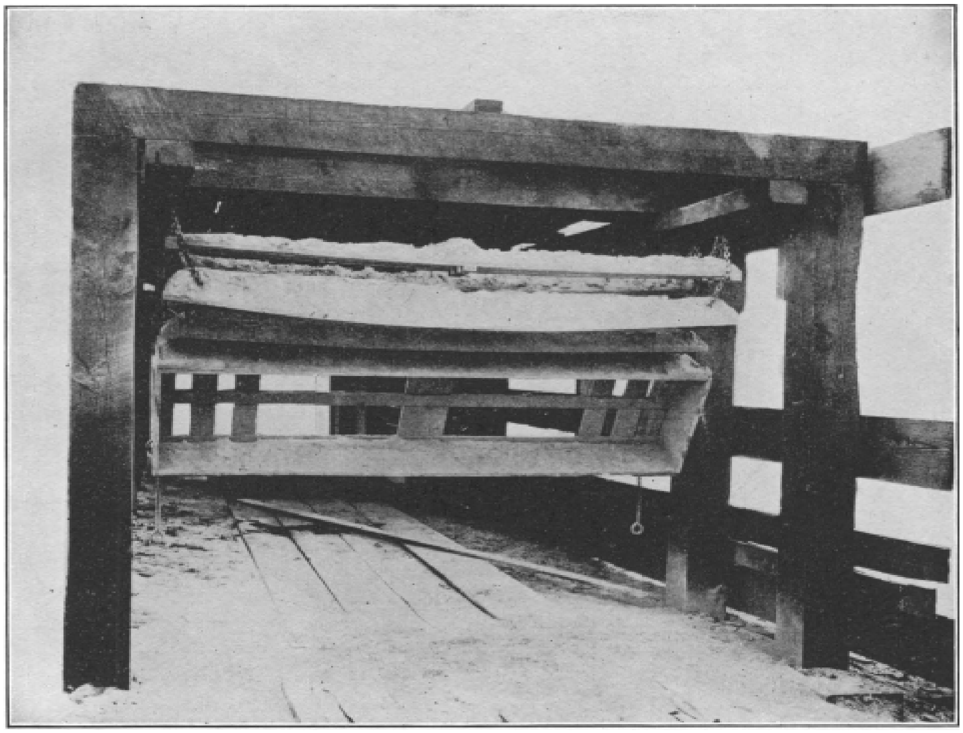

Figure 2.6 Model C Box Barrier after Dumping [Rice et al. 1922].

Other methods that were tested included the use of v-shaped troughs that consisted of twelve (12) inch wide boards that were nailed together at right angles, because of the ease with which the trough could be constructed a large number of tests were conducted using this design. The v-trough operated in a similar manner to the box-A barrier, but was easier to construct and install in the entry. Another tested method was the use of concentrated barriers supported by a system of hinges and catches that would swing open when air pressure reached a predetermined amount [Rice et al. 1922]. The concentrated barriers had the best results of any alternative method tested, however, they presented a safety risk to miners. Accidental operation of these barriers and the falling of large quantities of dust could injure anyone who happened to be passing under the barrier.

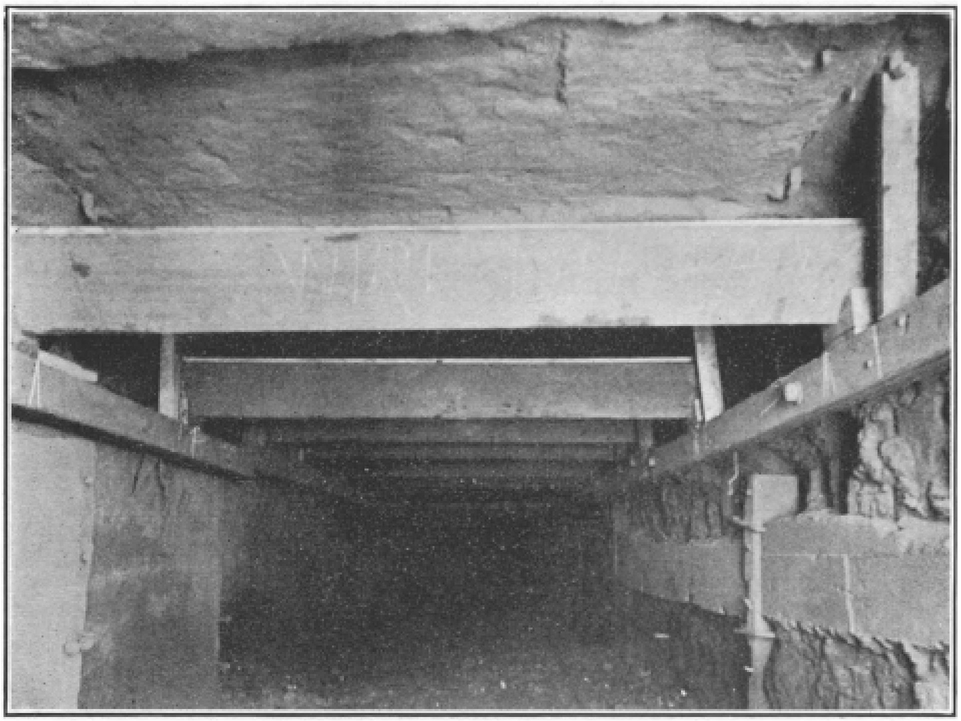

Figure 2.7 V-Trough Barrier Installed in Experimental Mine [Rice et al. 1922].

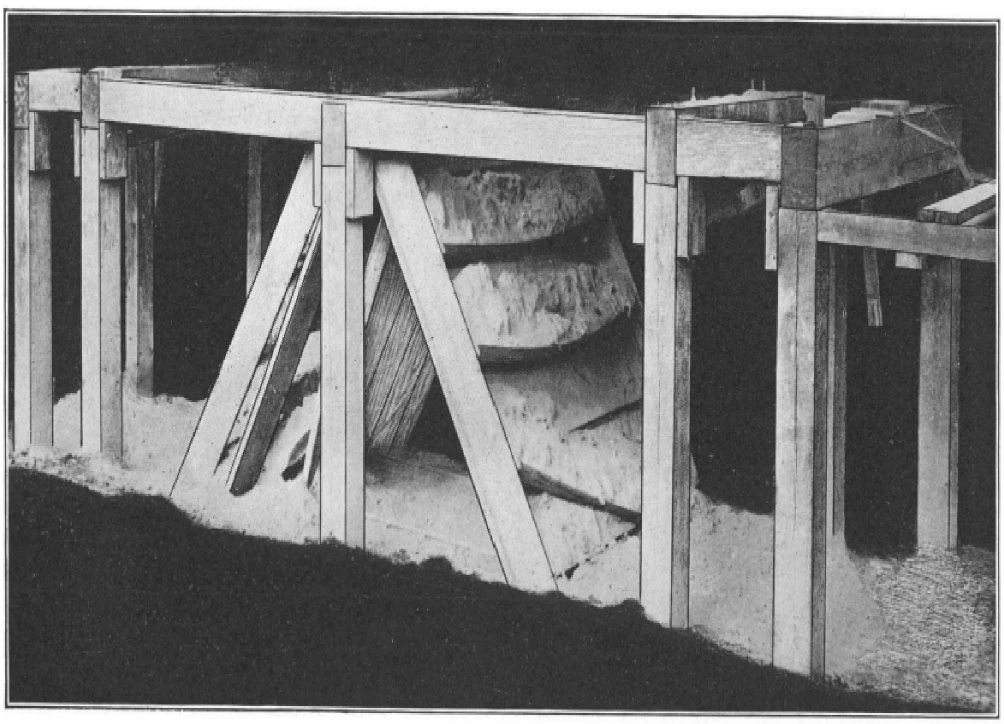

Figure 2.8 Side View of a Concentrated Rock Dust Barrier after Dumping [Rice et al. 1922].

These results indicate that the latest types of barriers that were tested in each design could successfully suppress a flame front in almost all conditions. However, the possibility of an explosion being inadequately suppressed was still present within the results of the tests. These methods were recommended to only be used as supplementary methods of safety to ensure that an explosion was adequately suppressed. The BoM still recommended that the safest methods to ensure proper suppression of flame front were the use of general continuous rock dusting or the use of a mine-scale watering system. These methods were designed to replace the continuous dusting method. Future research conducted by the bureau was concerned with using machines to aid the continuous dusting process.

By the late 1930s the preferred method of applying rock dust was through a mechanical distributor. The basic principle of all mechanical distributors at the time was the same. An air current was created using a fan into which rock dust is continuously fed. The discharge of these distributors was through either fixed openings or through the use of a flexible pipe [Greenwald 1938]. However, Greenwald states that dusting by hand still had definite use in protecting a mine from explosions. At the time three different manufacturers had marketed permissible distributors for underground mines, but they had two common limitations. Each of these distributors required rail track and electrical power in order to operate. This made dusting by hand the only method available for entries that did not have rail track installed, or in cases were electrical power was unavailable. These issues were significantly more problematic for smaller mines that could not afford a rock dusting machine, or the production delay associated with hand dusting.

The last alternative methods that were tested by the BoM sought to remediate the issues that these smaller mines were facing. The first method involved the use of permissible explosives to disperse rock dust into the entries. This method was tested using 0.5 pounds of a gelatinous permissible explosive placed underneath a fifty (50) pound bag of rock dust. In total, fifteen (15) tests were conducted at the Bruceton experimental mine for permissible explosives. Each test consisted of a group of five (5) explosive-rock dust combinations placed on twenty (20) foot intervals. After the test was conducted, the weight of dust that was dispersed on to the floor, roof, and ribs was calculated. All tests conducted with permissible explosives used a total of 400 pounds of rock dust. Using this information, the mean dust dispersal in pounds per linear foot of entry was calculated to be 2.82 [Hartmann et al. 1950].

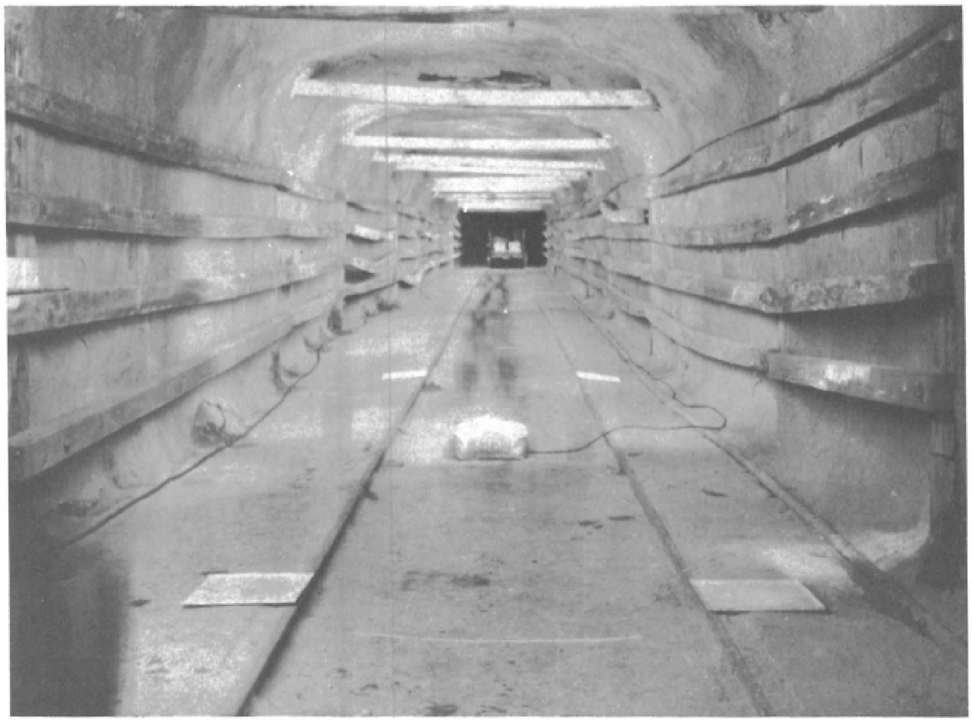

Figure 2.9 View of Mine Entry Before Rock Dusting by Aid of Permissible Explosives [Hartmann et al. 1950].

Figure 2.10 Mine Entry After Rock Dusting by Permissible Explosive [Hartmann et al. 1950].

The results of the explosive dispersal were compared to machine dispersion and hand dispersion along the same length within in the same entry. A typical commercial high-pressure rock dusting machine was used with standard industry practice. The machine traveled slowly up the entry against the air current. The rock dust was blown through the hopper and applied to the exposed surfaces through a flexible hose. These tests again used 400 pounds of rock dust so that a direct comparison of the dispersion methods could be made. The average dust dispersion for machine application as found to be 2.43 pounds per linear foot. The final test conducted was to rock dust forty (40) feet of entry by hand using a total of 160 pounds of rock dust. The average for these tests was found to 2.9 pounds per linear foot [Hartmann et al. 1950].

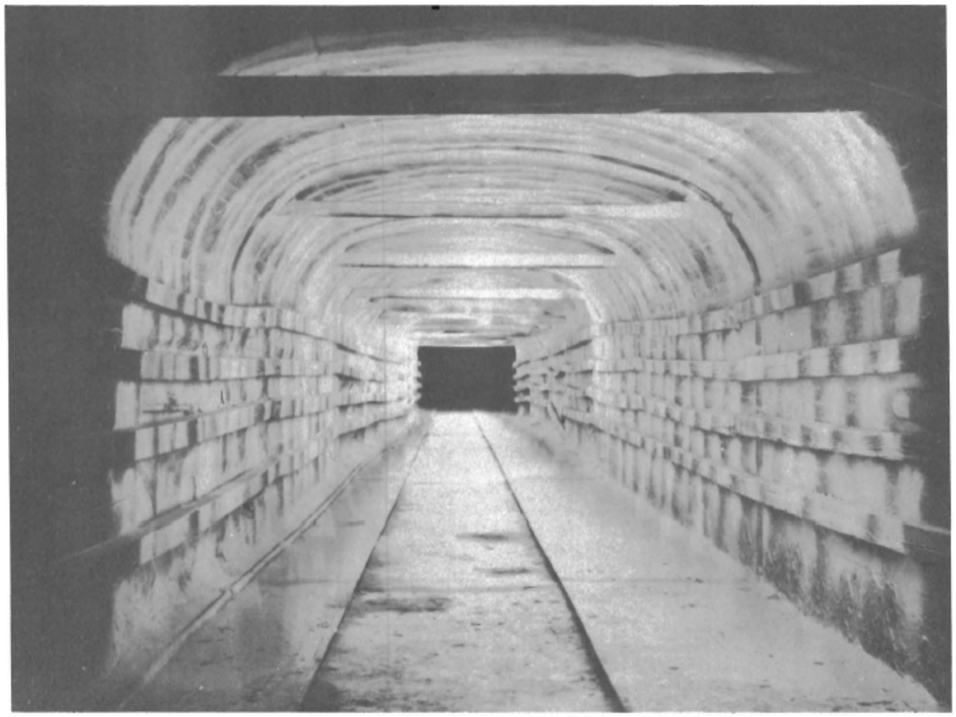

Figure 2.11 Mine Entry After Rock Dusting by Machine [Hartmann et al. 1950].

The results of this testing indicate that the total dust dispersed along the entry using permissible explosives was comparable to the two common industry methods. However, it was noted in the results of the permissible explosives experiments that an only an average of 18 percent of the dust that had been dispersed into the entry was found on the roof and ribs of the entry. The remainder of the dust had simply settled on to the floor of the entry. The results of hand dusting were slightly improved, an average of 23 percent was found on the roof and ribs. The best results came from machine application were 35 percent of the rock dust was found on the roof and ribs, which indicates a more uniform distribution of the dust than the other two methods [Hartmann et al. 1950]. Another concern for the researchers was the possibility of an accidental ignition of a gas-air mixture using the permissible explosives. In investigating the possibility of an accidental ignition, six (6) guidelines for use of permissible explosives were produced by the BoM. These guidelines include:

1. Explosive gas mixture detection
2. Explosive amount per delay
3. Floor geologic conditions

4. Amount of rock dust used per shot
5. Placement of the rock dust bag to completely cover the explosive charge
6. Use of two competent men to place, and perform the shot.

Ultimately, the use of permissible explosives to distribute rock dusting was considered a possible safety hazard, and was not recommended by the bureau for use in commercial applications. Another common practice for smaller mines was to use bag-type rock dust barriers suspended from the roof of mine entries. The fundamental concept was that the explosive shockwave and ensuing flame front would cause the rock dust bags to tear open and disperse their contents. However, it was found that they were ineffective without a device that ensured good dispersion of the rock dust across the entire entry.

The final alternative method that was tested by the BoM was the incorporation of a “burster” device in the suspended rock dust bags. The bursters used for these bags consisted of a permissible gelatinous explosive that was placed centrally within the bag. Fifteen (15) trials were conducted with bursters. Six (6) trials were conducted with two connected bags of rock dust that were placed in the entry on a twenty (20) foot interval. The remaining nine (9) tests were conducted using single bags that were placed on ten (10) foot intervals. In total, only two (2) of these trials were considered a failure were the rock dust failed to suppress the flame front, and both of these failures were from the single bag trials

Figure 2.12 View of Room with Double Bag Rock Dust Units [Hartmann et al. 1950].

.

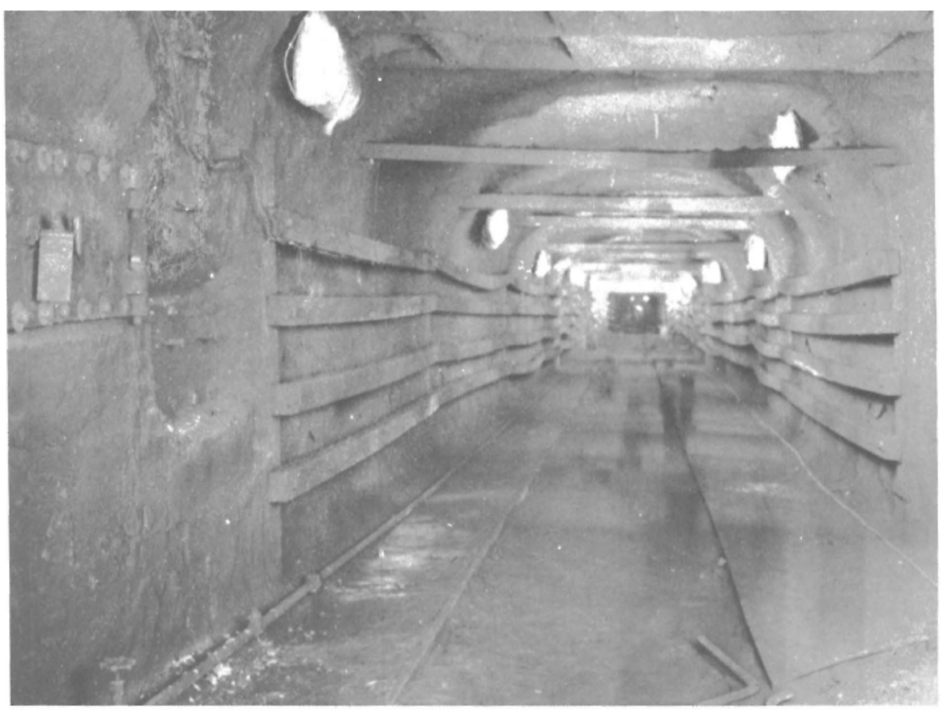

Figure 2.13 View of Main Entry with Single Bag Rock Dust Units [Hartmann et al. 1950].

The use of burster devices in rock dust bags was proven to be a successful method for suppressing a flame front, however it saw limited application around the U.S. This was primarily due to the belief that the permissible explosive contained within the rock dust bag could accidentally operate and trigger a gas-air mixture within the mine. Another contributing factor was the continued mechanization of the mining process. Rock dusting machines were developed that were did not require rail track.

2.4 Development of Wet Dust

The requirement for rock dusting to be practiced to within a minimum of forty (40) feet of all working faces created the need for a rock dust that could be applied during production shifts. This was significantly important for mines that were early adopters of a mechanized mining process, where continuous miners could advance several hundred feet in a shift [Hartmann and Westfield 1956]. Rock dusting was a very dusty process that could impede the mining process, and more importantly, adversely affect the health of the miners. This caused some mine's rock dusting efforts to fall behind the advance of the faces, which could potentially leave hundreds of feet unprotected at a time. The first solution to this method was the concept of pretreating the exposed surfaces of the entry with water before applying rock dust. This would improve the adherence of the rock dust, and prevent the dust from traveling down the ventilating current to the active face.

Two methods were tested to wet the surfaces before the application of rock dust. The first method involved using a water spray for ten (10) minutes before applying the rock dust. The second was by attaching a water spray at the front of the nozzle on the rock dust hose, so that the water would reach the surface slightly ahead of the rock dust [Hartmann and Westfield 1956]. These tests utilized two types of limestone rock dust. Ordinary limestone dust is designated as Limestone A, and limestone that has been surface-treated (the process and chemical used to treat the limestone is not disclosed within the document) is designated as Limestone C. The results of these tests clearly indicate that for both limestone types, wetting the surface increases the adherence of the rock dust. Nominal dust concentrations were taken for both types of limestone. Figure 2.14 shows the corresponding graph when plotting the concentration of dust adhering to the roof and ribs of the mine and the total amount of dust that was applied in the entry.

When comparing the results of the two dust types, the ordinary limestone dust performed better for both dry and wetting applications. The bureau stated that it was advisable for commercial mines to wet the exposed surfaces to increase adhesion, however there were no specific guidelines published for wetting surfaces. Instead, the bureau recommended using a trial and error basis for selecting appropriate available limestone dusts and wetting times.

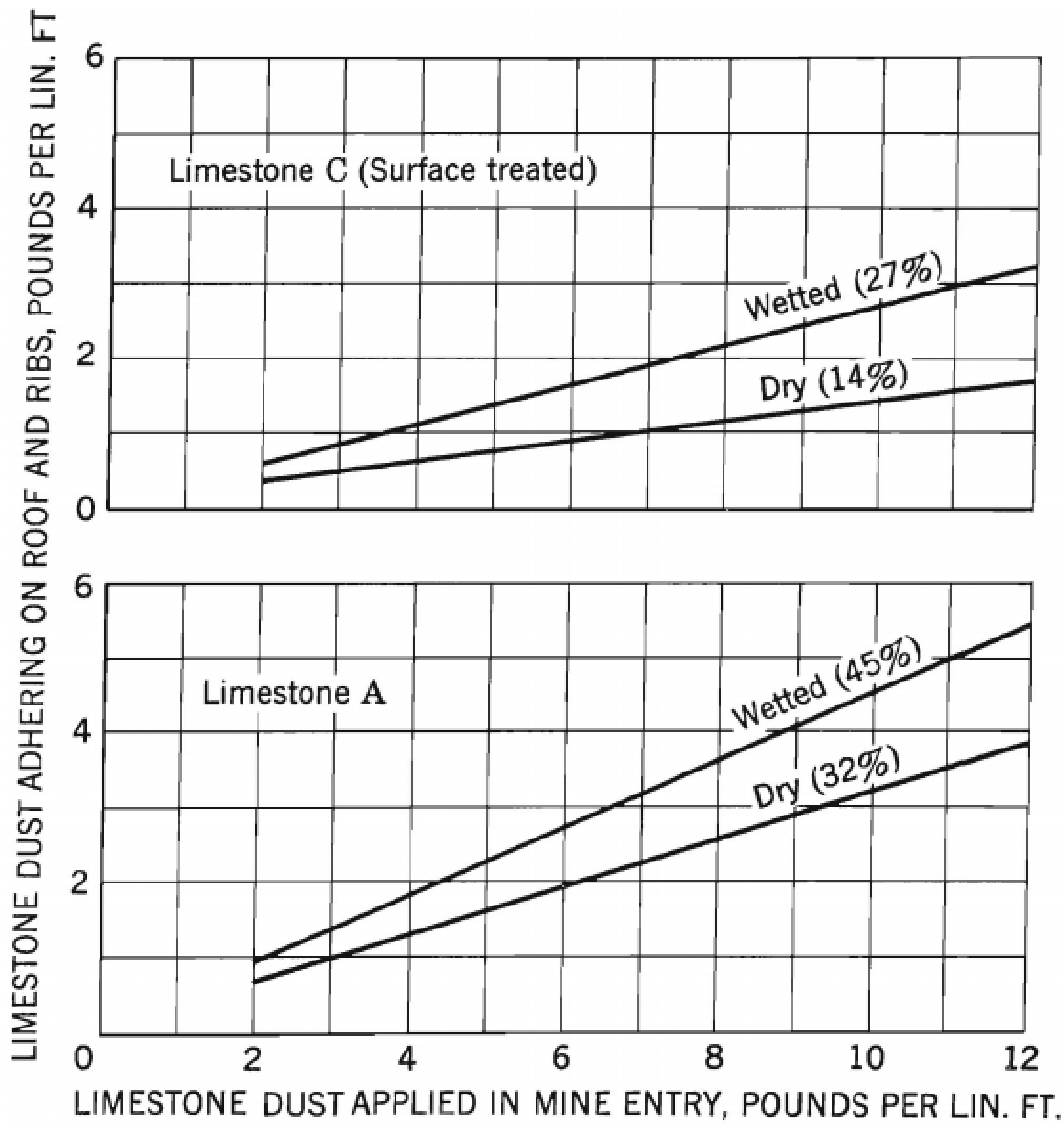

Figure 2.14 Adherence of limestone dust on dry and wetted surfaces of mine entry [Hartmann and Westfield 1956].

These previous methods involved applying water to dry rock dust. An alternative method that was investigated was the creation of a premixed water/rock-dust slurry that could be pumped through a mechanical distributor. The reasoning behind this method was to combine the increased adhesion that had been found by wetting the surfaces prior to dust application, and eliminate the necessary wetting time period that was required. This would allow rock dusting to be performed during production shifts, and reduce the possibility of an unsuppressed explosion. An experiment was conducted at the Bruceton experimental mine to assess two aspects of wet rock dusting. The first objective of the research was to determine if wet rock dust could be practically applied in commercial coal mines with acceptable adherence. The second objective was to study the effectiveness of wet rock dust, after it had partially or completely dried, in suppressing the propagation of an explosion [Hartmann and Westfield 1956].

The results of this preliminary study showed that premixed rock dust slurry could effectively be fed through a typical mechanical distributor. To achieve proper and effective rock dusting a minimum of four (4) pounds of rock dust per linear foot was required. The most effective slurry consisted of fifty (50) pounds of water mixed with 100 pounds of limestone dust. With this mixture approximately 85 percent of the rock dust adhered to the roof and ribs of the entry. Float rock dust concentrations were compared between standard dry dust and the slurry mixed rock dust.

> Using standard commercial practices, the dust concentration twenty-five (25) feet downstream was found to be as high as 5,000 million particles per cubic foot of air, and 100 feet downstream the count was about 2,000 million particles per cubic foot. When the slurry was applied, the dust count was less than 0.5 percent of the foregoing values [Hartmann and Westfield 1956].

Given the results of the preliminary testing the next step was to assess the explosion suppressing capabilities of the wet rock dust.

The explosion tests used to test this new rock dust application technique were performed in the main entry of the experimental mine. Two ignition methods were used in this experiment. The first method used a blown-out shot fired from the face of the entry into an area of pulverized coal dust; the second method was the ignition of a twenty-five (25) foot long gas-air mixture near the face of the entry. The rock dusted zone started approximately fifty (50) feet from the ignition point at the face. This distance was used instead of the required forty (40) feet due to the physical dimensions of the entry. The wet dust was applied only to the roof and ribs of the entry, standard dry rock dust was used for the floor. Once the wet rock dust had been applied, a small amount of coal dust was dispersed over the rock dusted zone. This was done to simulate float coal dust that would be deposited on the entries during operation [Hartmann and Westfield 1956]. The results of the tests concluded that wet rock dust could be used to suppress an explosion. However, there are noted issues with rock dust performance once it has encountered and retained moisture. After a rock dust has become moist, the dust agglomerates into clumps through a process known as caking. Caking has negative effects on the performance of rock dusting. Previous research conducted by the BoM has shown that testing results were uniformly negatively impacted by the presence of water in contact with rock dust [Rice et al. 1911, Rice, Jones 1915, Rice et al. 1922, Hartmann and Westfield 1956].

The caked rock dust would not be readily dispersed into the entry as compared to normal rock dust. Caking also has adverse effects on the ability of rock dust to suppress the flame front of an explosion. Rock dust that is suspended in the mine entry following an explosive shockwave acts as a heat sink for the combustion reaction of coal dust. The reduction in effective surface area will impede the heat transfer, and cause the explosion to propagate a greater distance into a rock dusted zone before there is insufficient energy to cause combustion of the suspended coal dust.

Caking is not unique to rock dust. The aggregation and caking processes of granular materials is well documented issue that causes many problems in many operations including: (1) food, (2) fertilizers, (3) pharmaceuticals, and (4) soils. Caking has two primary causes, which are compressive and moisture migration caking [Christakis et al. 2006]. Rock dust caking is primarily related to the latter of these causes. Moisture migration caking is broken down into five stages:

1. Wetting and moisture absorption
2. Liquid bridging
3. Drying and moisture desorption

4. Hardening and solid bridging
5. Compacting and caking

The process of bridging occurs after the rock dust particle surfaces have become hydrated by artificial or mechanical wetting or through environmental moisture absorption. Water particles create a connection between the individual rock dust particles through cohesion and adhesion. These bridges allow for the molecules within the rock dust particles to flow. When the rock dust particles begin to dry, material suspended within the liquid bridge experiences recrystallization and creates a solid bridge between the particles [Christakis et al. 2006]. When the rock dust is exposed to a cycle of wetting and drying the solid bridges that are formed will strengthen and reduce the space between the rock dust particles creating an agglomeration of particles. This agglomeration is referred to as “caked” rock dust in industry, and is recognizable by the distinct clumps of rock dust.

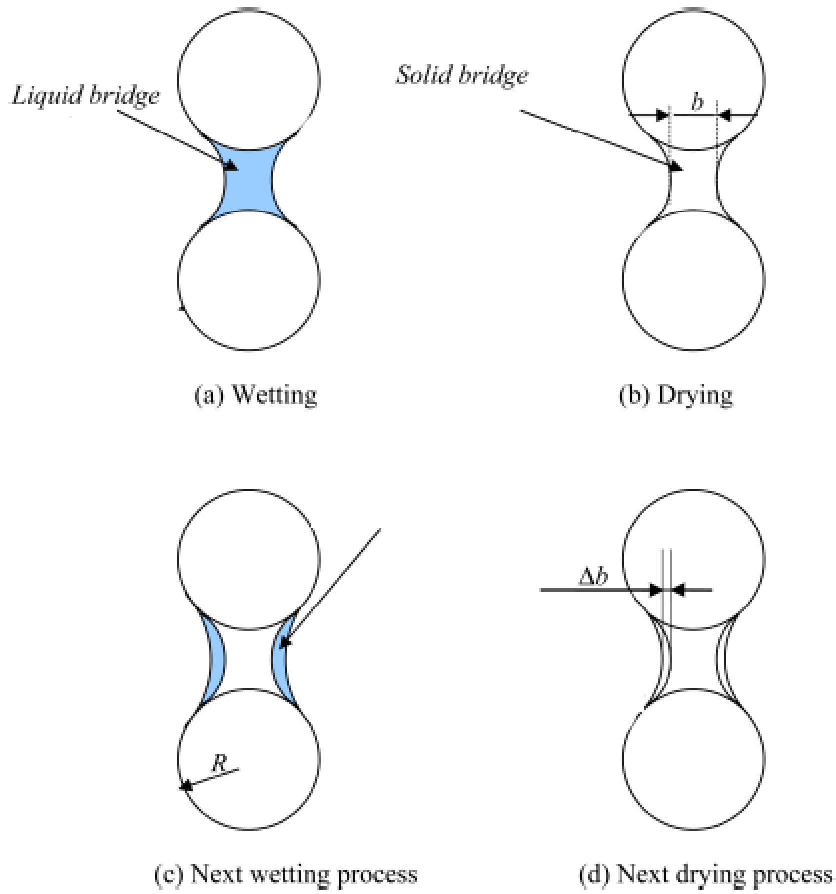

Figure 2.15 Schematic Diagram of Solid Bridge Formation and Caking During a Wetting/Drying Cyclic Process [Christakis et al. 2006].

2.5 Hydrophobization and Polymerization of Rock Dust

Reducing or eliminating the effect of caking has been extensively studied by the mining industry and other industries where undesirable caking can occur. Historically, the solution to this problem was the creation of a hydrophobic surface that would repel water. A more recent, innovative approach to this problem utilizes polymer chains that attach to the exposed surfaces of the rock dust particles. This prevents the attachment of water molecules due to a lack of sufficient space on the rock dust particle. The creation of a hydrophobic surface on rock dust particles has been researched extensively throughout the 20th century.

The fundamental concept of hydrophobization is the creation surfaces that will repel water and prevent the formation of the liquid bridges that will allow material to flow between particles [Huang et al. 2015]. Preliminary hydrophobicity tests were conducted in the late 1930's by the BoM [Greenwald, 1938]. Through the use of chemical additives, the properties of the exposed surfaces of the rock dust particles could be modified to reduce water absorption [Greenwald, 1938]. A number of reagents including: stearic, palmitic, and oleic acid have been studied and have been proven to provide waterproofing effects to rock dust particles [Huang et al. 2015].

The most recent studies related to the hydrophobization of rock dust particles use oleic acid and its salt sodium oleate. Hydrophobicity is indicated by contact angle measurements of water molecules and the rock dust particles. The normal contact angle between rock dust and water is 0°, however with addition of oleic acid or sodium oleate the contact angle is continuously increasing [Huang et al. 2015]. Three concentrations of oleic acid were selected: 0.5, 1.0, and 2.0 lbs. / ton rock dust. These three concentrations were also used when measuring the contact angle for sodium oleate; in addition, a fourth concentration of 1.5% by mass of sodium oleate was also tested. This final concentration was used to create a super-hydrophobic surface which has exaggerated water repelling properties, but this concentration was not used in any further testing because it was thought to be unreasonable from an economic perspective.

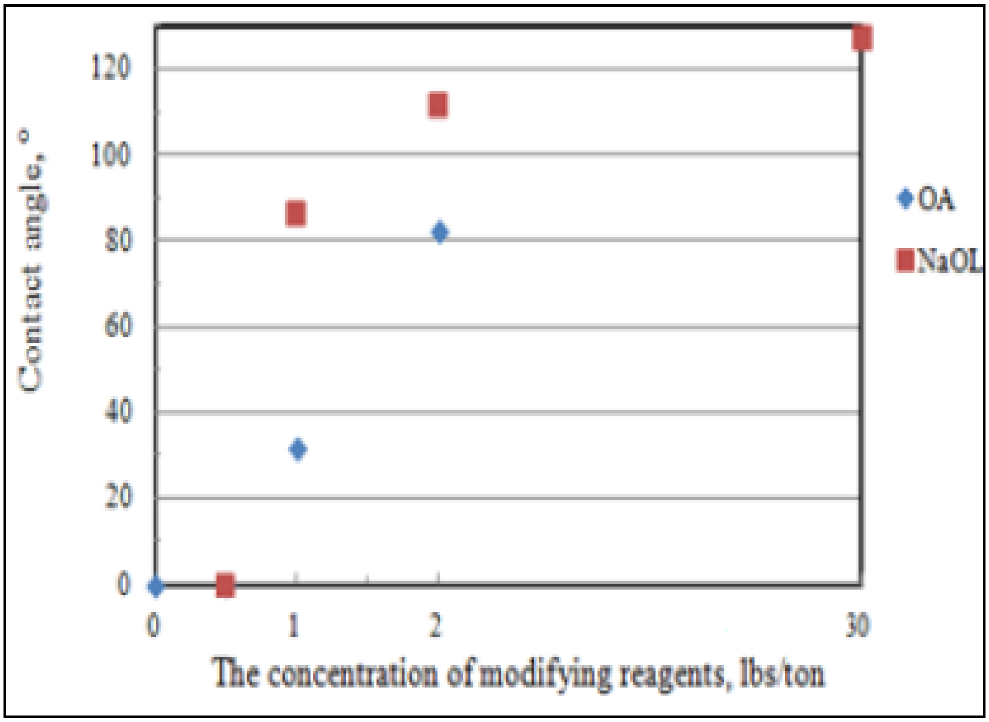

Figure 2.16 Contact Angle as a function of OA and NaOL concentrations [Huang et al. 2015]

Moisture desorption tests were also conducted to determine the rate at which samples would partially and completely dry. In total, fourteen (14) rock dust samples were tested in this experiment. Each previously mentioned concentration of oleic acid and sodium oleate was used along with unmodified wet rock dust. The samples were placed within a Caron environmental chamber that was set to a constant temperature of 20° Celsius and 80 percent relative humidity. The samples were removed daily and the weights were recorded. The moisture desorption was calculated as the difference between the initial weight and the daily recorded weights. Figure 2.17 shows the resulting moisture desorption as a function of time. Each data point represents the average of the two samples that were prepared using the specified concentration [Huang et al. 2015]. The results of the experiment show that the drying time required to achieve equivalent levels of moisture desorption was decreased with increasing concentrations of both oleic acid and sodium oleate, however sodium oleate had marginally improved performance when compared to oleic acid.

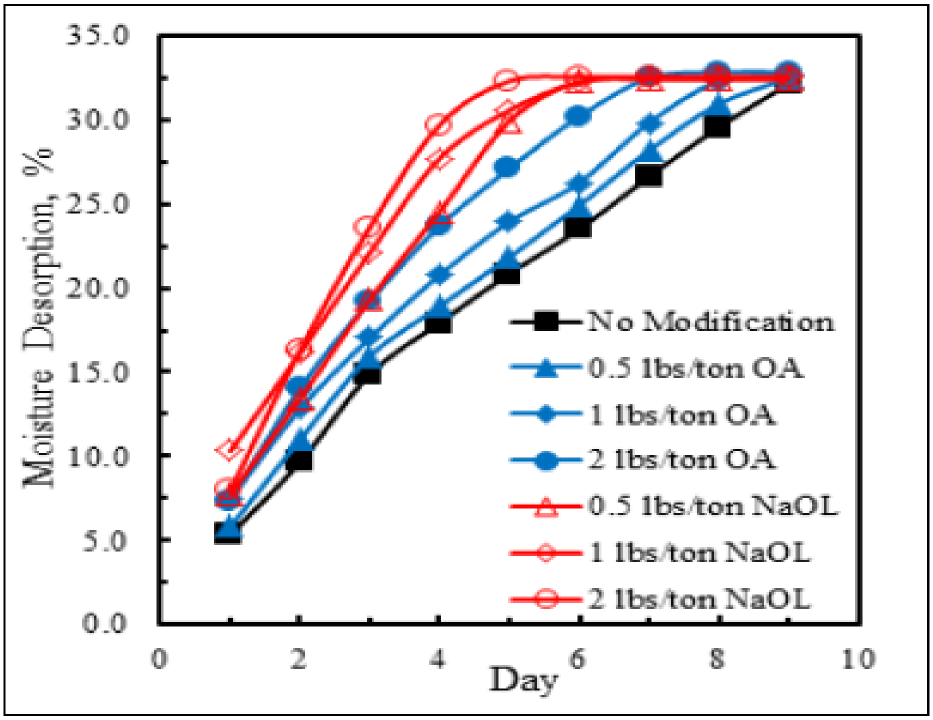

Figure 2.17 Moisture Desorption Rates in an Atmosphere of 20° C and 80% Relative Humidity [Huang et al. 2015].

Explosibility tests were performed using hydrophobic rock dust samples that were created using an identical process. These samples were tested along with other types of rock dust and the results of these explosibility tests are presented and discussed and compared in detail in a later chapter of this work. Another method that has been less extensively research is the creation of polymer chains within the rock dust that will prevent the absorption of water by causing the rock dust particle to attach to a large polymer chain causing insufficient space for the water molecule to attach.

Two (2) of these that are discussed in this work are Dywidag Systems Internation (DSI) DYWI dust, and Strata Worldwide FoamDust. The DYWI rock dust is created through the use of chemical additives that would allow for non-respirable place of rock dust without the use of pre-generated foam [Pinkley et al. 2012]. The FoamDust is created using a similar process. These dusts were also tested in this research and the results are compared to the hydrophobic dust and the standard industrial rock dusts.

2.6 Explosibility Testing with Rock Dust

The effort to update the technical specifications of rock dust in terms of sizing and incombustible content is directly correlated to the increased understanding of the explosibility of coal dust/ air mixtures. Throughout the 20th century, the bureau conducted numerous theoretical and experimental studies. The purpose of these studies was to further understand the flammability behavior of substances for an accurate assessment of the explosion hazards associated with these mine atmosphere mixtures. The first set of tests that were conducted by the BoM used homogeneous mixtures of mine gases, which produced satisfactory results to obtain general consensus of the associated explosion hazards. However, these tests failed to clearly assess the hazards associated with a heterogeneous mixture of gases and dust, which is typical of underground coal mining conditions. Previous data that had been produced for these mixtures was diverse and largely inconclusive due to the unique procedures and data collection techniques for each experiment [Hertzberg et al. 1979].

Research was conducted by the BoM during the latter half of the 20th century to standardize the testing apparatus and procedure used in these flammability tests. The first apparatus used in these experiments was approximately 8 liters in volume, and was based upon the chamber that was used by the bureau for homogenous gas mixtures for explosibility studies [Hertzberg et al. 1979]. The initial tests in this research used the following procedure. A known mass of dust was spread around the dispersion cone at the bottom of the chamber. Pressurized air was then ejected radially to lift the dust. A continuous ignition source was continuously activated during this dust dispersion. Results were reported in terms of nominal concentrations where a direct calculation was made between the mass of dust divided by the chamber volume. However, it was generally realized that the dust dispersion for this chamber was not uniform [Hertzberg et al. 1979]. A second iteration of these experiments used an optical probe within the explosive chamber to measure the concentration at designated points. In these tests, Pocahontas and Pittsburgh coal dust were used.

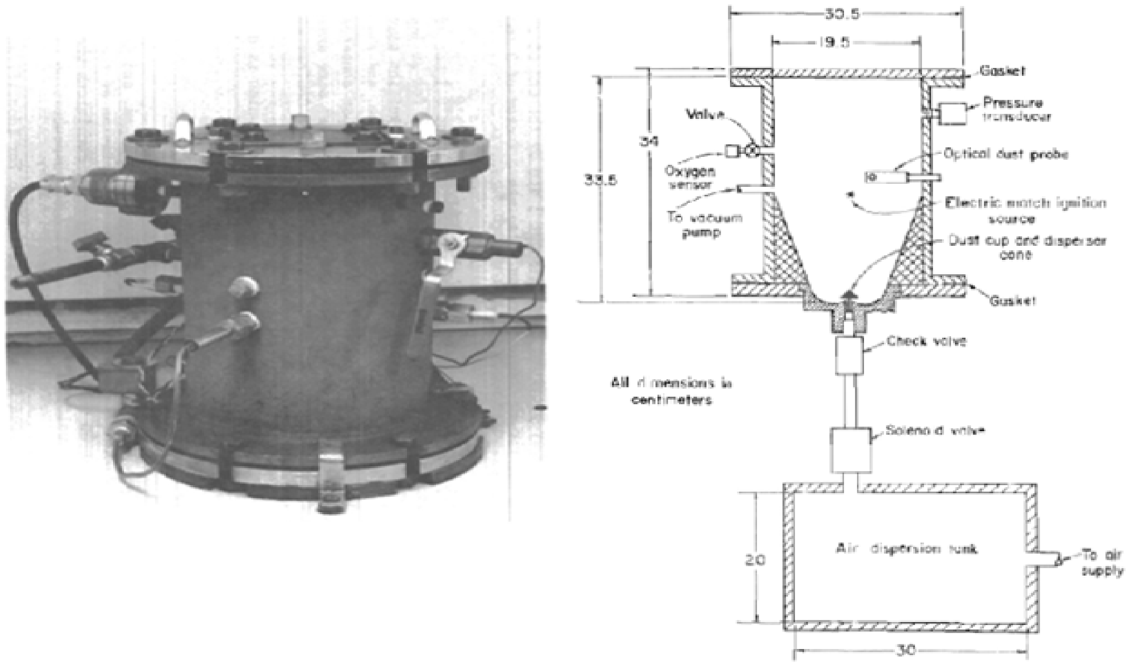

Figure 2.18 Modified Hartmann chamber used to study the flammability of air-dispersed dusts [Hertzberg et al. 1979].

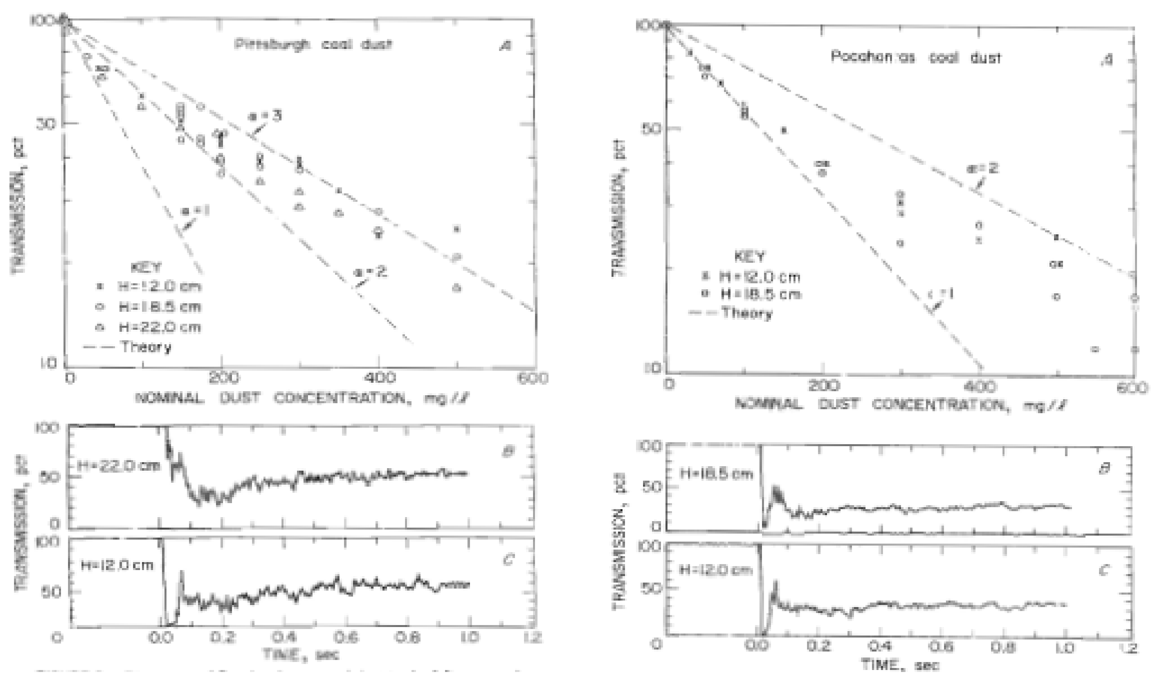

Figure 2.19 Nominal dust concentrations and optical probe transmission for Pocahontas and Pittsburg dusts [Hertzberg et al. 1979].

The data obtained from these tests showed good agreement with full-scale mine explosion testing results (Fig 2.19). However, the chamber was limited by the maximum ignition energy that could be realized within the relatively small volume. To increase the ignition energy, two larger volume chambers were constructed. In Europe, a 1-m^3 was designed by Bartknecht, which became the standard chamber that was used for measuring pressure and pressure rates. However, in the U.S., a 20-L spherical chamber was designed by Siwek which gave comparable data results. This larger volume chamber was adopted by the BoM as the standard apparatus for dust flammability testing. This chamber was constructed of 304 steel, with a pressure rating of 21 bar (304.5 psi , 2100 kN/m^2). The dust was placed in a reservoir at the bottom of the dust chamber. Pressurized air is injected into the chamber and the dust is dispersed from the nozzle. Optical dust probes monitor the dust dispersion within the chamber.

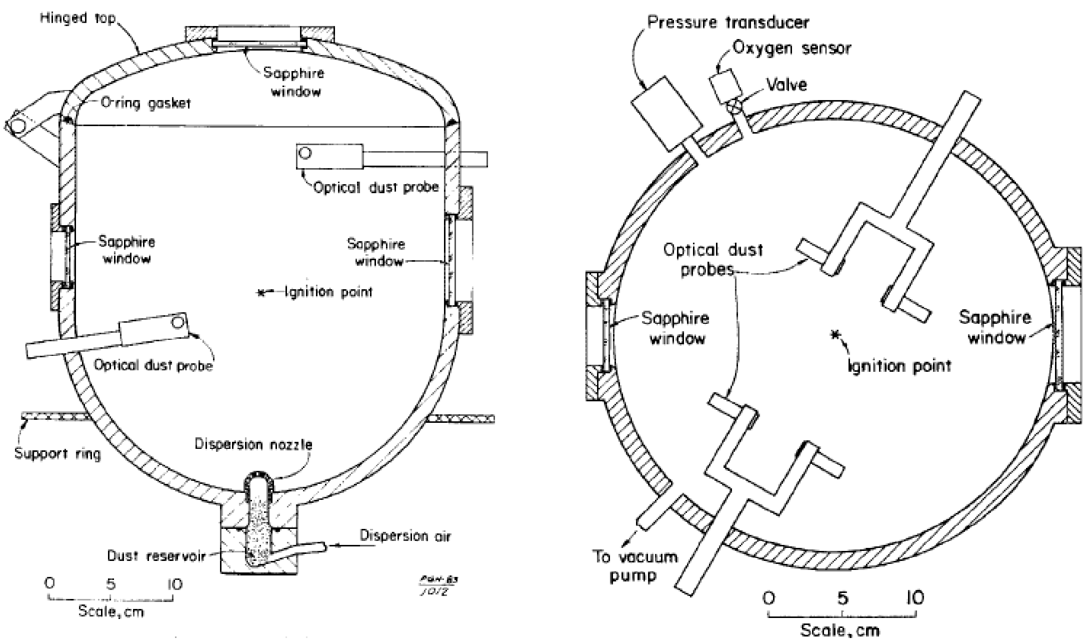

Figure 2.20 Vertical (left) and Horizontal (right) cross sections of the 20-L Explosibility chamber [Cashdollar, Hertzberg 1985].

A series of tests were conducted using the coal dust from the Pittsburgh coal seam. The tests were designed to determine the lean flammability limit of pure coal dust by measuring the pressure ratio and the volume-normalized pressure rise within the chamber. The pressure ratio is defined as the peak explosive pressure divided by the ignition pressure. The ignition pressure for all these tests was at 1 atm, and therefore the pressure ratio is simplified to the peak explosive pressure. A moderate level of air turbulence was used to simulate the standard air flow conditions of an underground coal mine. The results of the tests can be seen in Figure 2.21.

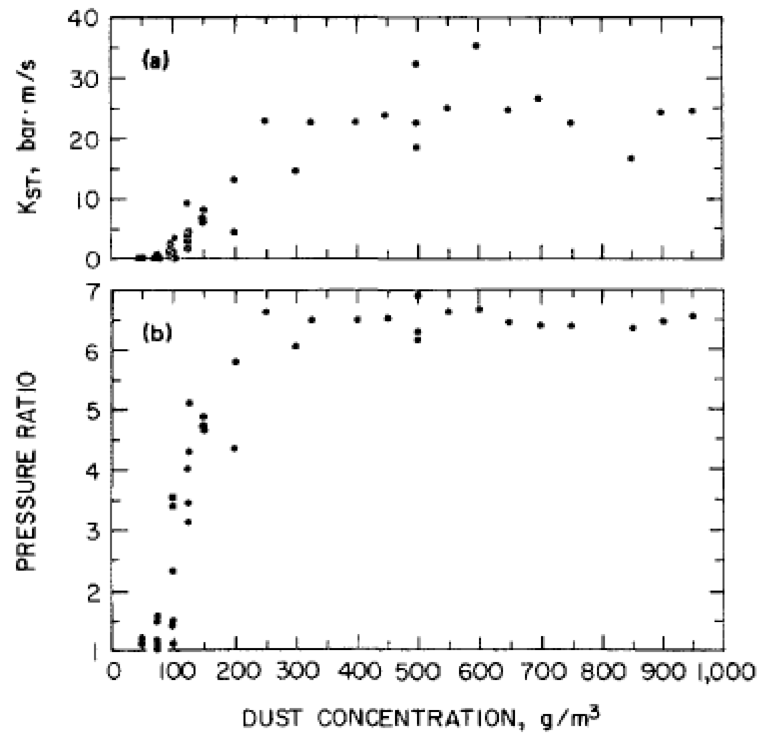

Figure 2.21 Explosibility Data for Pittsburgh Seam Bituminous Coal Dust in Air at a Moderate Turbulence Level [Cashdollar, Hertzberg 1985].

The rate of pressure rise (dP /dt) follows the cubic law index [Cashdollar, Hertzberg 1985]:

$$K_{st} = \left(\frac{dP}{dt}\right) V^{\frac{1}{3}} \qquad (1)$$

Using this data, further experimentation with the 20-L chamber with lean limit and ignition energies yielded the bureau's criteria for significant flame propagation. These two standards are based off the pressure ratio and the rate of pressure rise reference in equation (1). The two criteria for significant flame propagation are as follows: (1) the pressure ratio must be greater than 2.0 bar, and (2) the volume-normalized pressure derivative must be greater than 1.5 bar m s^{-1} [Hertzberg et al. 1988]. These two criteria were officially adopted by the BoM because they clearly differentiated between the ignitibility characteristics and the flame propagation characteristics. Previous research had failed to clearly mark this minute but significant difference. Using these two criteria the technical specifications for incombustible content in the atmosphere was updated from the requirements set by the Coal Mine Health and Safety Act of 1969. Subsequently, these criteria were also adopted by NIOSH after the closure of the BoM in 1995.

2.7 Respirable Dust and MSHA Final Rule

As mining has continued to become an increasingly mechanized industry, there has been a marked decrease in mean particle size. Coal dust particle size surveys have been conducted over the latter half of the 20th century, and the 21st century [Cashdollar, Hertzberg 1989; Amyotte et al. 1995; NIOSH 2010]. A detailed comparison of coal dust particles across the country was conducted by NIOSH in the early 2000s. In total, 217 samples were taken from sixty-one (61) bituminous coal mines as shown in Fig 2.22.

District	States	Mines	Samples	−270 mesh or < 53 μm, %	−200 mesh or < 75 μm, %	−140 mesh or < 106 μm, %	−100 mesh or < 150 μm, %	−70 mesh or < 212 μm, %	−50 mesh or < 300 μm, %	−40 mesh or < 425 μm, %	−30 mesh or < 600 μm, %	Dmed, μm
2	PA	6	20	23	29 ± 4	37	47	59	72	85	95	165 ± 27
3	OH, MD, No. WV	7	22	26	33 ± 9	41	51	62	74	87	96	149 ± 42
4	So. WV	7	23	25	30 ± 6	38	48	60	73	87	97	165 ± 39
5	VA	6	20	25	31 ± 8	40	50	62	74	86	96	157 ± 36
6	Eastern KY	5	24	25	31 ± 7	39	49	59	72	85	96	160 ± 37
7	Central KY	5	19	29	34 ±10	43	53	62	74	86	95	140 ± 48
8	IN, IL	6	18	24	29 ± 5	37	47	57	71	85	96	170 ± 31
9	CO, NM, UT	7	20	21	27 ± 3	36	46	57	71	85	96	172 ± 26
10	Western KY	5	28	23	29 ± 4	39	50	61	74	86	96	152 ± 24
11	AL	7	23	30	37 ± 10	48	60	73	84	92	97	128 ± 46
	10 Districts Average		**217**	**25**	**31**	**40**	**50**	**61**	**74**	**86**	**96**	**156**

Figure 2.22 Average coal sizes from intake airways in mines in 10 MSHA Safety and Health Districts [NIOSH 2010].

Similarly, particle size surveys were conducted for return airways from thirty-six (36) bituminous coal mines. The results of this analysis corresponded with the results of the intake airways with high amounts of particles smaller than a sieve having 270 openings per linear inch [NIOSH 2010]. The full data for the particle size analysis is included in Appendix A of this research. This changing mean particle diameter for coal has a direct correlation with the amount of rock dust and the mean particle diameter for rock dust.

Previous research has demonstrated that the inerting requirement for a give coal particle size decreases as the mean diameter of the rock dust decreases. This is because of the corresponding increase in surface area of the rock dust. However, altering the particle size of the coals has a dramatic effect on the inerting requirements. A small decrease in mean particle size of coal dust results in a substantial increase in the amount of limestone that is required to inert the mixture [Amyotte et al. 1995]. Therefore, in order to effectively rock dust a coal mine entry to ensure flame suppression requires both more rock dust and finer rock dust particle sizes when compared to original size surveys conducted by the BoM in the 1920s. However, this decreasing particle size leads to other health concerns for miners working in these conditions underground, particularly related to the issue of respirable dust.

Respirable dust is defined as that particle size which can penetrate the upper respiratory system and deep into the lungs. These particles that penetrate into the lungs are beyond the natural respiratory clearing mechanisms and are likely to be retained within the lungs for a prolonged period of time. Of particular concern is free silica particles which have been shown to remain in the lungs almost indefinitely and can lead to debilitating lung diseases. Ventilation research has long been concerned with threshold limits of various gases and dusts, and research has shown that respirable dust has an upper limit of seven (7) micrometers in diameter. This is shown with several other common ventilation aerosols in figure 2.23.

Type of aerosol	Size range in microns (10^{-6} m)	
	Lower	Upper
Respirable dust	-	7
Coal and other rock dusts	0.1	100
Normal atmospheric dusts	0.001	20
Diesel particulates	0.05	1
Viruses	0.003	0.05
Bacteria	0.15	30
Tobacco smoke	0.01	1
Pollens causing allergies	18	60
Fog	5	50
Mist	50	100
Light drizzle	100	400

Figure 2.23 Size ranges of common aerosols [McPherson, 2009].

As the mean particle diameter of rock dust continues to decrease in order to adequately suppress an explosion, the concern for respirable dust exposure has increased. The exposure limit prior to 2014 was designated as a time-weighted eight (8) hour average of 2.0 milligrams per cubic meter. This limit value is only true when the values of free silica are below 5%, when this value is exceeded the limit value is reduced by the following equation:

$$TLV = \frac{10\frac{mg}{m^3}}{\%\ free\ silica} \qquad (2)$$

A separate limit is implemented for miner's that have shown significant signs of development of debilitating lung disease, referred to as part 90 miners. Individuals in this category have a time-weighted eight (8) hour average of 1.5 milligrams per cubic meter. However, over the decade of 1995-2004, more than 10,000 U.S. coal miners died from black lung. Additionally, young miners continue to show evidence of advanced and seriously debilitating lung disease from excessive dust exposure [MSHA 2014].

In response to the findings from these studies conducted by NIOSH, MSHA enacted a final rule to change the permissible dust exposure levels for all miners. On August 1, 2014, the Mine Health and Safety Administration (MSHA) issued a final rule to lower miners' exposure to respirable coal mine dust. Major provisions of the rule were set to promulgate over the next twenty-four (24) months. At the end of this period the final rule will be in effect which lowers the concentration limits for respirable coal mine dust. The overall dust standard is reduced from 2.0 to 1.5 milligrams per cubic meter of air, and from 1.0 to 0.5 milligrams per cubic meter of air for part 90 miners [MSHA 2014].

CHAPTER 3 EXPERIMENTAL SETUP AND SAMPLE PREPARATION

3.1 Experimental Setup

Three experiments were conducted in this research. The first experiment measured the explosibility of various coal dust concentrations. This was done to select appropriate sample sizes for the flame quenching experiments. The second experiment measured the ability of the rock dusts to suppress a flame front before significant propagation. To perform both of these experiments, two separate but similarly outfitted 38L explosive chambers were used in the flame quenching experiments. A "black" chamber was initially used, and a secondary "gray" chamber with a slightly different design which did not alter the testing methodology was constructed and used in later testing. The chambers were designed similarly to the chamber used by the USBM and NIOSH for dust testing experiments (Siwek 1985). The test apparatus consists of: 38L explosive chamber, 200 psig pressure reservoir, vacuum pump, and electronic controls for air injection and ignition.

The second experiment measured the angle of lift and the lift velocity of the rock dust sample after an explosive shockwave had passed. To accomplish this experiment the following equipment was used: two free-field pressure sensors, a high-speed camera, velocity screen with 1ft intersections, a C4 explosive charge, and the shock tube located at the University of Kentucky Explosive Research lab in Georgetown, Kentucky. Table 3.1 summarizes the experiments that were conducted in this research.

Table 3.1 Summary of Experiments

Test	Purpose	Pertinent Measurements
Coal dust alone	Establish baseline for future test configurations	Peak explosive pressure (psia)
Flame quenching tests	Determine if explosion was suppressed before significant propagation	Peak explosive pressure (psia) Volume-normalized rate of pressure rise (bar m s^{-1})
Angle of Ejection	Measure effect of caking and effective dispersion	Angle of dust lift (deg) Lift Velocity (ft/sec)

3.2 Sample Preparation

Flame extinguishing tests were prepared by placing the prepared sample into a steel tray. The tray was enclosed on three sides by a lip with a height of 0.4in (10mm) or 0.8in (20mm). Two different tray types were selected to determine if there were significant dispersion differences based on lip height. The larger lip was also needed to properly contain the larger volume samples which are discussed in more detail in a later section of this thesis. The samples were all prepared in accordance with Title 30 of the Code of Federal Regulations Section 75.403. This regulation states that the minimum incombustible content of applied rock dust is 80%. Areas where methane is present in a ventilating current will require an increase of 0.4% incombustible content for each 0.1% increase in methane content. Two sample configurations were used in these tests. The first configuration used sixty-four (64) grams of rock dust with sixteen (16) grams of coal dust. The second configuration used increases these quantities by a factor of two, resulting in 128 grams of rock dust and thirty-two (32) grams of coal dust. These sample configurations were chosen based on the necessity to test if sample size would affect test results. Additionally, the sample container volume prohibited the use of larger sample sizes.

All trials of the explosion suppression experiments were prepared in a laboratory at the University of Kentucky using the following materials. The coal dust used is Pittsburgh Pulverized from Hadsell Chemical. The rock dust used in these experiments is MineBrite G260. This rock dust is produced by Huber Engineered Materials from the Marble Hill Plant located in Marble Hill, Georgia. Particle size analysis was conducted on the material that was received from Huber Materials, and showed that 92.69% of the material passes a 200 mesh sieve. This indicates that the rock dust meets all requirements of current MSHA regulations.

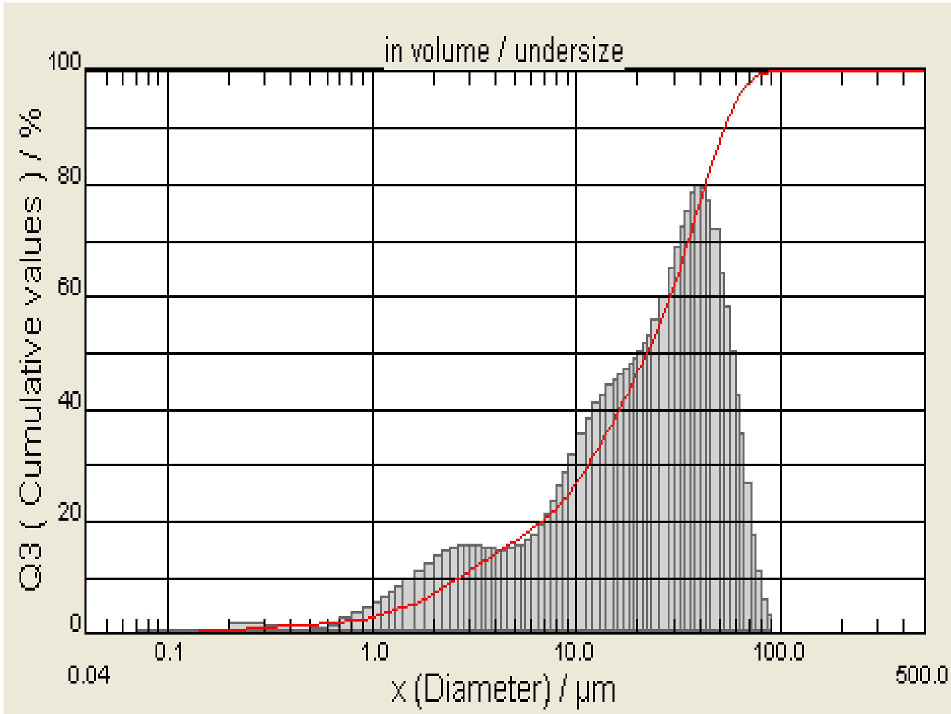

Figure 3.1 Particle Size Analysis for MineBrite G260

All samples were prepared in a similar manner. Wet dust samples were created using a rock dust to water weight ratio of 2:1. This ratio was selected because it is commonly used in industry applications of rock dust. To prepare the wet sample, dry rock dust was poured into a large container, and then the appropriate amount of water was added to the rock dust. The sample was then thoroughly mixed for fifteen (15) minutes. The mixture was then poured into the steel tray. The FoamDust was created in a similar process with dry rock dust and water being mixed together, but the chemical additives were also added at this point in amounts per the manufacturer's recommendations. According to the Material Safety Data Sheet (MSDS) provided by the manufacturer, the chemicals are classified as a minor skin and eye irritant. DYWI dust samples were created and provided to the research team by DSI. The MSDS obtained for this indicates that the chemical additives are noted as a moderate skin irritant and eye irritant. The MSDS recommends the use of proper eye protection, and the use of rubber or PVC gloves when handling the chemical additives for both of these rock dusts. Furthermore, the chemical additives used in both of these are dust are not listed as a toxic material according to the USEPA, and do not need to be reported to the toxic release inventory as of the most recent update to this inventory in March 2015. Due to proprietary information concerns, the specific chemical additives that are used in the creation process cannot be fully disclosed at this time. but they are not listed as a toxic material according to the USEPA

Samples were left to cure for a seven (7) or fourteen (14) day period. During this time, the samples were subjected to typical temperature and humidity conditions for an underground coal mine as measured at an underground coal mine in Eastern Kentucky. Figure 3.2 shows a period of twenty-two (22) days at the Eastern Kentucky coal mine. The readings for temperature and humidity were taken every hour. The yellow line displays the relative humidity, and the white line represents the temperature. Figure 3.3 shows a sample of typical dry dust after curing for a seven day period.

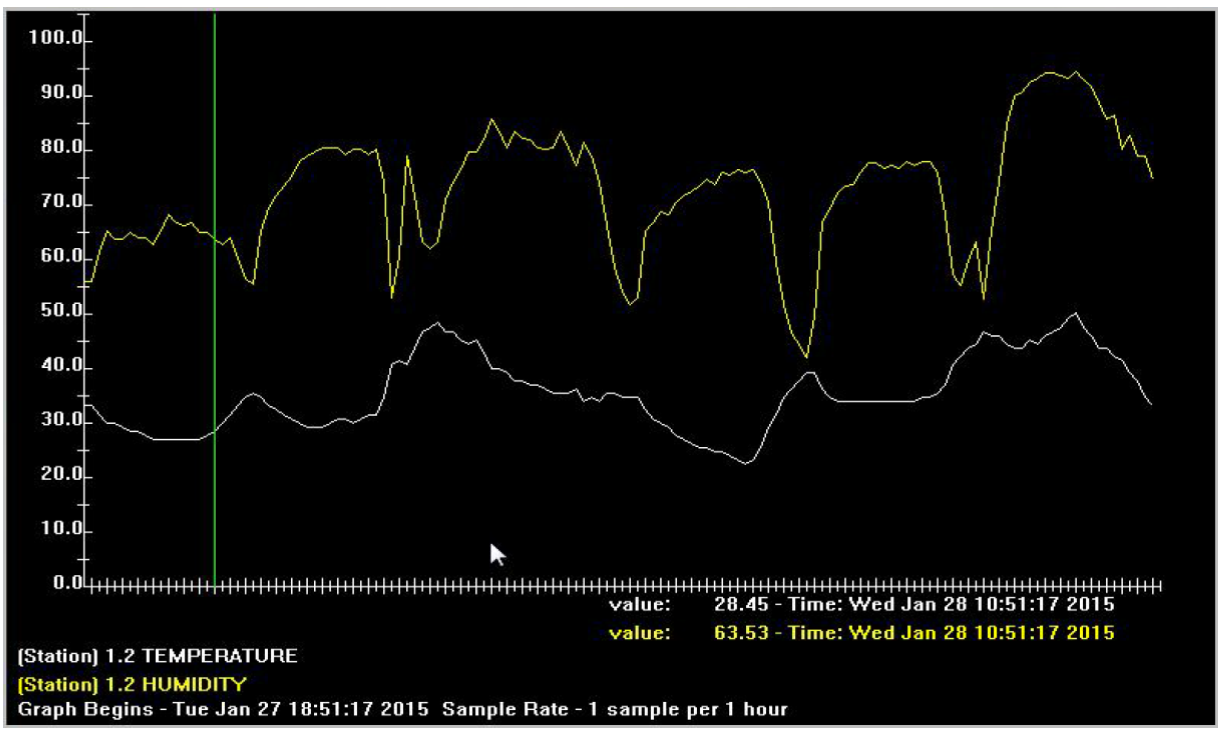

Figure 3.2 Typical Temperature and Humidity Cycle

Figure 3.3 Sample of dry dust after curing

3.3 Flame-Extinguishing Test Method

After the samples had cured for the appropriate time period to become at equilibrium with the environment (i.e. no weight change over time), the flame quenching characteristics of the rock dust were ready to be determined. The first step was to measure the weight of the sample and then pour the correct amount of coal dust on top of the rock dust sample. This was done to simulate the float coal dust from active mining that has settled in the return airways which play a significant role in flame propagation. The sample was then installed in the test chamber, along with a 5kJ Sobbe igniter, and then sealed. The vacuum pump was then activated, and the chamber was drawn down to a pressure of approximately 2 psia; during that time, the pressure reservoir is filled to 140 PSI. A vacuum was necessary because as air was injected into the sealed chamber to disperse the sample, the interior pressure would rise. The interior pressure was constantly monitored to where the blower was shut off and the igniter was detonated when atmospheric pressure (~14.7 psia) was reached. The pressure reservoir is required to inject pressurized air to disperse the sample after the vacuum has been created. The pressure reservoir should be filled to approximately 140 psig to ensure proper dispersion of the sample to recreate a typical float dust mine atmosphere [Cashdollar 1989].Figure 3.4 shows the original 38 L explosive chamber that was used in the explosion suppression experiment. Figures 3.5-3.9 show the various steps taken to prepare the sample and to ensure that all conditions are met before the test is conducted.

Figure 3.4 38 L Explosive Chamber

After all conditions had been checked, software was used to start the test. The solenoid valve opens, and compressed air is injected into the chamber causing the rock and coal dust to disperse within the chamber. When the pressure within the chamber has reached atmospheric level, 14.7 psia, the solenoid valve closes, and the 5kJ igniter then detonates. The software package used in this test records the pressure within the chamber during all phases of the experiment.

Figure 3.5 Float coal dust placed on top of prepared rock dust

Figure 3.6 Sample tray installed in chamber

Figure 3.7 5kJ Sobbe igniter installed in chamber

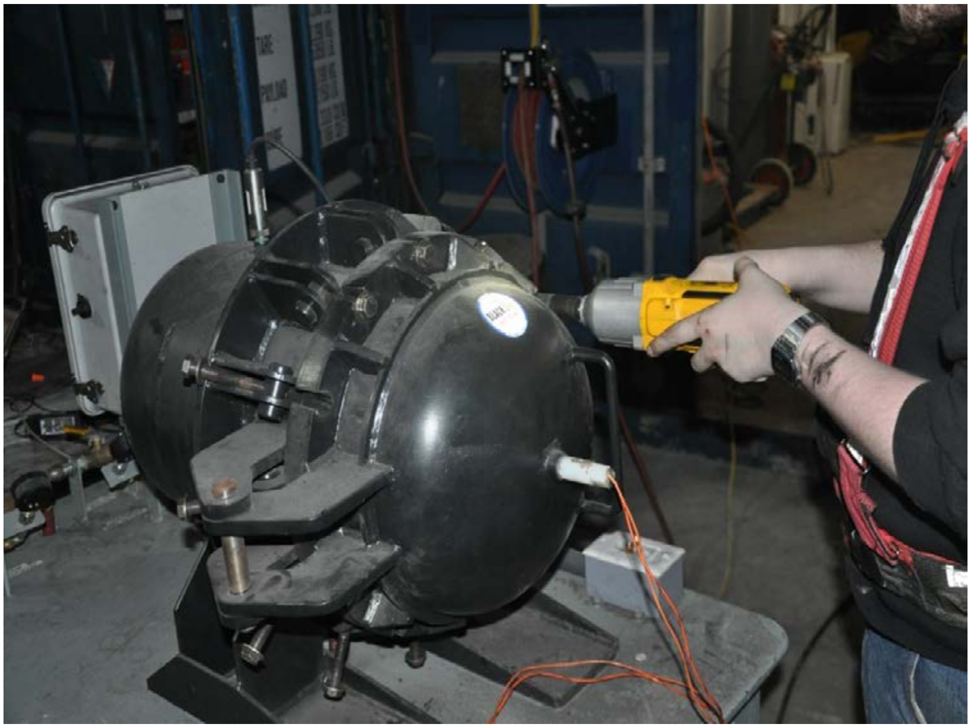

Figure 3.8 Chamber sealed

Figure 3.9 Pressure reservoir filled to 140 PSI

Once the test is completed, the chamber is then unsealed, and the tray is removed. The tray's weight is then recorded. The chamber and tray are then both cleaned thoroughly through the use of compressed air to ensure that subsequent testing is not affected by rock and coal dust that has adhered to the side of the test chamber from previous testing. After the chamber and tray have been cleaned, the testing method continues by repeating the above process. Figures 3.10 and 3.11 depict the final steps in the testing method for each rock dust sample. The data for each test is recorded and stored for future use.

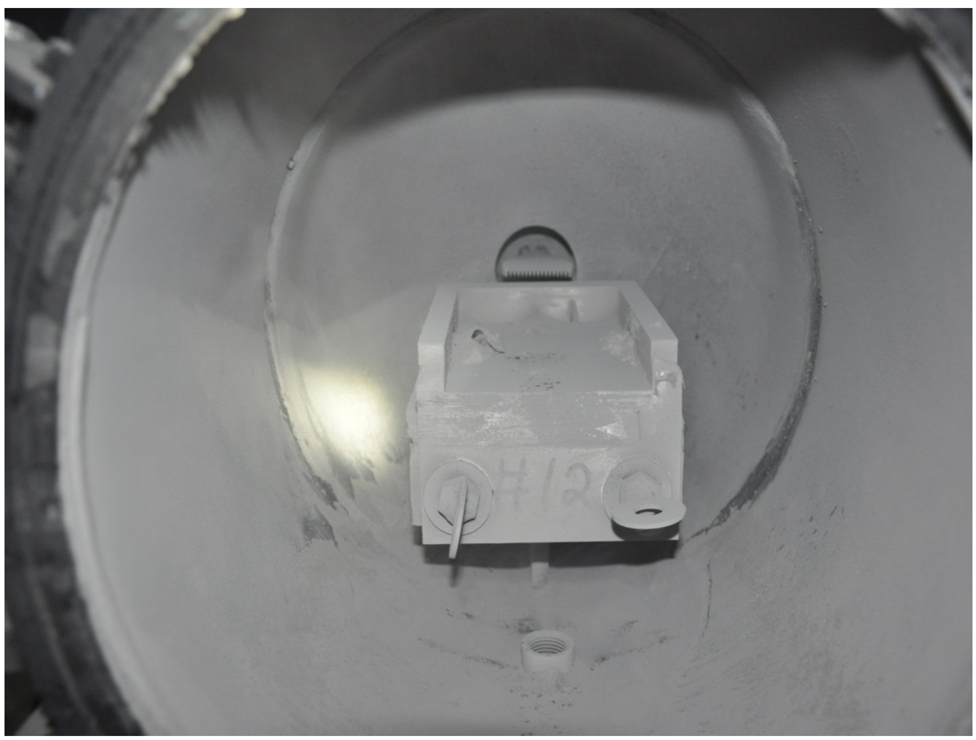

Figure 3.10 Chamber after test completion

Figure 3.11 Sample tray after test completion

CHAPTER 4 EXPLOSIBILITY TESTING

4.1 Coal Dust Explosion Tests

Tests were initially conducted to determine the explosibility curve of coal dust alone in the chamber used for these experiments. Various concentrations of coal dust were used to find amounts that would increase the possibility and intensity of an explosion. If an insufficient amount of coal dust was used in the test, then the sample would merely deflagrate. Data obtained from deflagration is not suitable to determine the extinguishing characteristics of the rock dust in the case of a detonation. This is due to the large pressure difference between deflagration and detonation. Previous literature related to rock dust testing has shown that there are two criteria for significant flame propagation of a coal dust sample. These are the maximum explosive pressure, $P \geq 2$ bar (200 kPa), and the volume normalized rate of pressure rise, $\left(\frac{dP}{dt}\right)V^{\frac{1}{3}} \geq 1.5$ bar ms^{-1} (150 kPa ms^{-1}).

In total, eight (8) different configurations were tested with coal dust alone. Each configuration had three (3) experimental trials, resulting in twenty-four (24) total tests. These tests used increments of 7.6 grams (0.017 lb.) of coal dust. When normalized to the 38 liter chamber, this results in concentration increments of 200 g/m^3 (0.012 lb/ft^3). The pressure values used to disperse the coal dust into the chamber remained constant at 150psi. Previous testing has indicated that a minimum pressure of 140psi is necessary to ensure proper dispersion within the chamber.

Based on the results of the coal dust testing, it was determined that a minimum concentration of 400g/m^3 (0.025 lb/ft^3) was required in order to meet the pressure rise criteria. This equates to a minimum amount of 15.2 grams (0.033lb) of coal dust. This was increased to a minimum amount of 16 grams to further increase the chance of detonation which equates to 421 g/m^3 (0.026 lb/ft^3). Figure 4.1 gives the maximum pressure values that were recorded in each of the tests. From this graph it is clear that for concentrations below 400g/m^3 (0.025 lb/ft^3) there was an increased chance of deflagration of the sample. Regression lines were then added that create the explosibility curve of the coal dust that was used in the testing. Based upon the data, and the regression curves, the team decided upon the two sample configurations: 421 g/m^3 (0.026 lb/ft^3) and 842 g/m^3 (0.053lb/ft^3). This second concentration was selected because the pressure values that were recorded for pure coal dust were spread across a wider range. This would give a wider range of pressure values for the rock dust to experience, and a more comprehensive test of the flame suppression capabilities of the rock dusts.

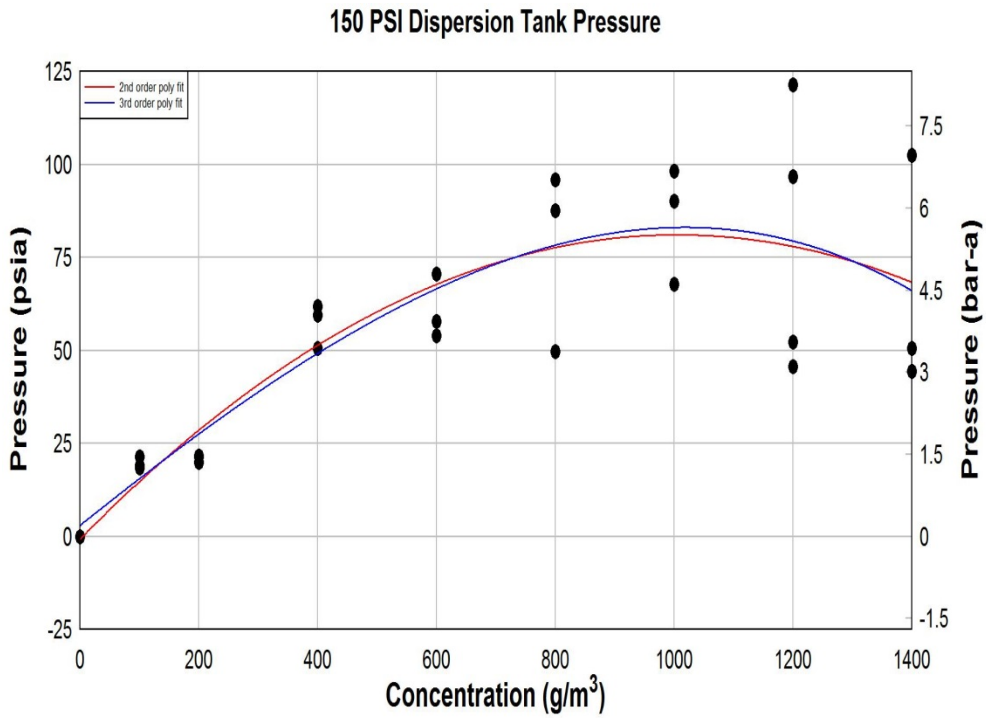

Figure 4.1 Coal dust explosion test peak pressures

4.2 Rock Dust Inerting Tests Results

Two sample configurations were selected based on the data from the explosibility curve testing. The first configuration selected used sixteen (16) grams of coal dust, and the second uses thirty-two (32) grams of coal dust. These two configurations yield concentrations of approximately 400 g/m^3 and 800 g/m^3, respectively. The research team decided that a larger sample size may yield different results, and that the larger sample size was more representative of situations that occur in an underground coal mine.

In total, ninety-five (95) inerting tests were conducted in either of the explosive chambers. Fifty-six (56) trials were conducted with a coal dust concentration of 421 g/m^3 (0.026 lb/ft^3), and the remaining thirty-nine (39) had a concentration of 842 g/m^3 (0.053lb/ft^3). Table 4.1 gives a breakdown of the number of trials that were conducted for each dust type. The raw data for each of the explosion suppression trials is provided in appendix B of this thesis.

Table 4.1 Summary of Inerting Trials

Rock Dust Type	Trials
Dry	32
Wet	18
Hydrophobic	26
FoamDust	7
DYWI Dust	12
Total	95

Tables 4.2 and 4.3 show the average results for the smaller and larger sample sizes used in this research, respectively. The column for initial weight is the recorded weight of the sample at the time that it was created. Hydrophobic and wet dusts have a higher recorded weight value at this time due to the presence of water in the sample. Pretest weight indicates the measure sample weight after the sample had cured for a set time period of seven (7) or fourteen (14) days. This curing time allows for the hydrophobic and wet dust samples to partially or completely dry before they were tested. Samples configurations are referenced based upon the weight of rock dust contained within the sample. This means that despite having an initial weight of 96 g, the wet and hydrophobic dusts are still compared to the 64 g recorded weights for the other dust types.

Table 4.2 Average 64 g Rock Dust Results

Average 64 g Sample Configuration Results					
Dust Type	Initial Weight (g)	Pretest Weight (g)	Posttest Weight (g)	Peak Pressure (kPa)	Rate of Pressure Increase (kPa m s^-1)
Dry	64.0	63.9	34.5	154	36.0
Wet	96.0	65.7	48.1	158	36.0
Hydrophobic	96.0	66.9	37.6	136	34.0
DYWI Dust	65.9	65.9	43.8	143	48.0
FoamDust	64.0	64.0	47.9	143	56.6

Table 4.3 Average 128 g Rock Dust Results

Average 128 g Sample Configuration Results					
Dust Type	Initial Weight (g)	Pretest Weight (g)	Posttest Weight (g)	Peak Pressure (kPa)	Rate of Pressure Increase (kPa m s^-1)
Dry	128	128	118	154	62.0
Wet	192	148	138	403	212
Hydrophobic	192	133	117	194	76.0
FoamDust	128	125	110	159	61.0

Based upon the data provided in Table 4.2, it is clear that all rock dusts tested were capable of suppressing an explosion before significant propagation had occurred. Furthermore, all five of the tested dusts had similar results in regards to peak explosive pressure. The pressure derivatives show a larger variance, however, they all still fall within the criteria for significant flame propagation. The trends shown in the smaller sample size is carried over into the larger sample size.

When inspecting the data for the larger sample size, the dry, hydrophobic and FoamDust dusts all perform similarly with little variation in either peak explosive pressure or pressure derivative. However, this is an issue with the wet dust samples. The average results from these tests indicate that the wet dust was unable to suppress the explosion before significant propagation. It is important to note that the samples of DYWI dust were not prepared by the research team and were instead provided by DSI for testing. The samples provided were only prepared using the 64 g sample configuration. Further analysis of each dust type should be conducted on a trial-by-trial basis. This will allow for a more comprehensive analysis of the data for each rock dust.

4.3 Typical Dry Dust

Typical dry dust tests performed as designed and expected. The dry dust testing was expected to have excellent flame-quenching properties, and this was demonstrated during the inerting tests. Over the thirty-two (32) dry dust trials, the peak pressure achieved within the chamber was 22.77psi or 1.57 bar. Figure 4.2 graphically shows the peak pressure for each dry dust trial that was conducted in this research. After first inspection, there appears to be no significant difference between peak explosive pressure and sample configuration.

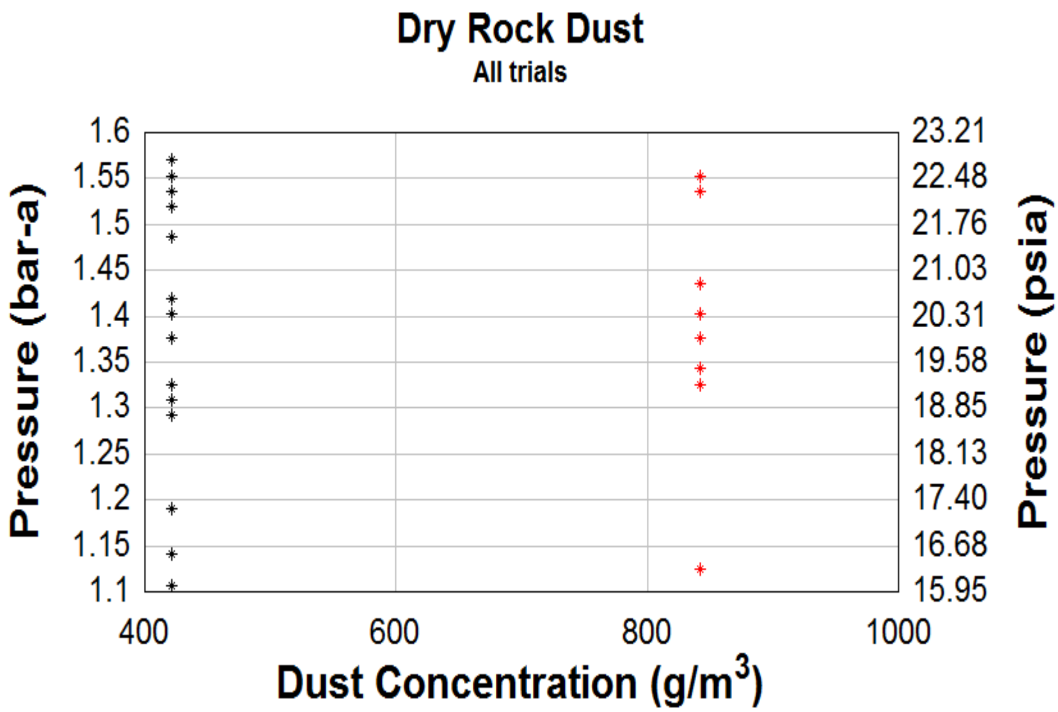

Figure 4.2 Peak explosive pressure for dry dust trials

Similarly, the maximum rate of pressure increase, across all dry dust experimental trials, was determined to be 65.0 kPa m s^{-1}. Figure 4.3 displays the recorded pressure and the rate of pressure increase for trial 042514_01. This particular trial experienced the highest recorded pressure, but the rate of pressure rise was only found to be 20.7 kPa m s^{-1}. The recorded pressure within the explosive chamber is shown by the black curve, and the rate of pressure increase is shown by the red curve.

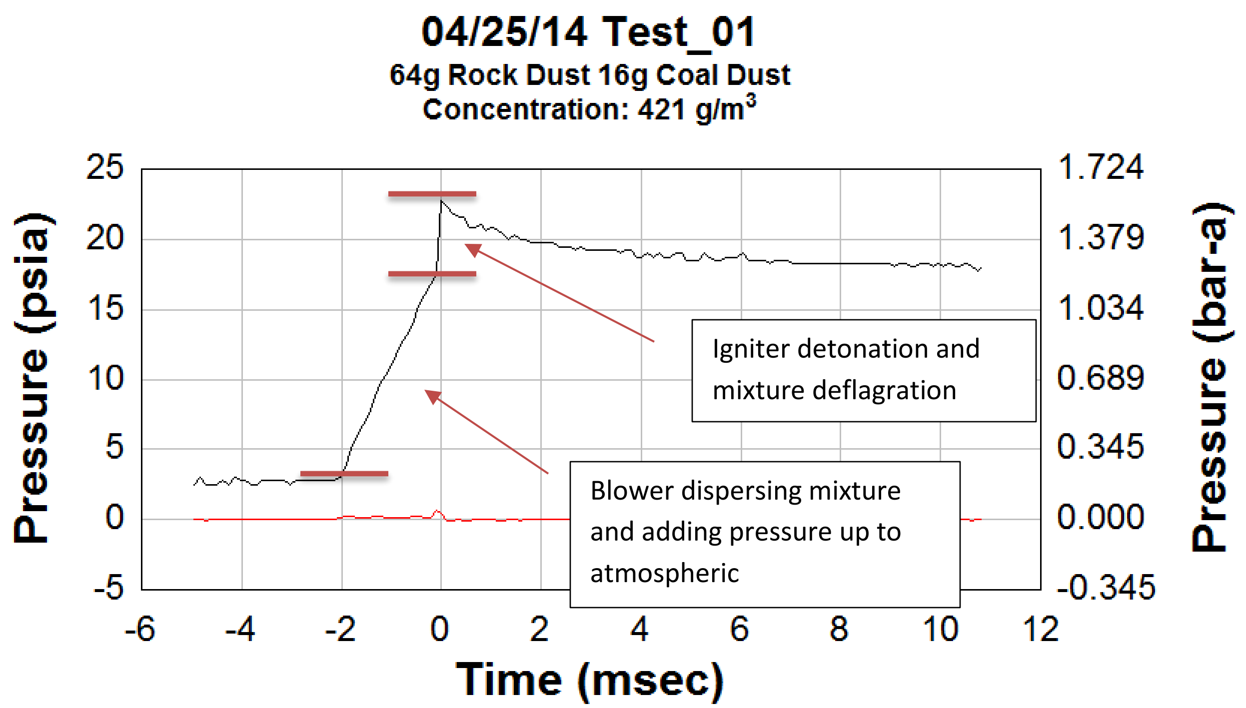

Figure 4.3 Worst case pressure values for typical dry dust with typical zones of blower dispersing mixture thereby increasing pressure and detonation of the igniter denoted.

For each trial of dry dust that was tested, the amount of mixture that was dispersed into the chamber prior to ignition can be calculated. This is useful to simulate how much rock dust would be liberated from an entryway (roof, ribs, or floor) during the event of a coal dust explosion. Across all thirty-two (32) dry dust trials, the average mixture dispersed into the chamber was 57.7%. This mixture represents the total amount of rock dust and float coal dust that has settled on top of the rock dust. When comparing the two sample sizes, the smaller sample size had higher weight dispersion with an average mixture dispersion of 61.4%. The larger sample size had a dispersion of 51.5%. The difference between these trials can most likely be attributed to the absorption of ambient water vapor at the test location and less mass to be dispersed for the same air pulse.

Table 4.4 summarizes the dry dust results. The sample weights were recorded prior to testing to determine if water had been absorbed by the rock dust during the curing process. This could cause some deviation in behavior due to caking. Based on this data, the dry dust prevents significant flame propagation. Neither of the two previously mentioned criteria was met, and therefore, the dry dust has prevented the propagation of a coal dust explosion.

Table 4.4 64 g Dry Dust Sample Results. Note the thresholds are 200 kPa and 150 kPa ms^{-1} for the peak pressure and rate of pressure increase, respectively.

Dry Dust 64 g Sample Configuration					
Trial Number	Initial Weight (g)	Weight prior to test (g)	Weight posttest (g)	Peak Pressure (kPa)	Rate of Pressure Increase (kPa m s^-1)
042514-01	64.0	64.0	57.1	157	20.7
042514-02	64.0	64.0	53.0	114	21.5
042514-03	64.0	64.0	57.1	155	65.0
042514-04	64.0	64.0	57.6	133	19.0
042514-05	64.0	64.0	57.2	149	58.9
042514-06	64.0	64.0	44.3	138	21.1
052114-11	64.0	64.5	30.4	138	38.1
052114-12	64.0	64.6	16.9	152	24.0
052114-13	64.0	64.8	16.2	119	21.4
052114-14	64.0	64.7	22.2	142	20.3
052114-15	64.0	64.7	8.8	131	21.4
052114-A1	64.0	63.0	17.7	133	7.1
052114-A2	64.0	63.2	19.7	142	16.6
052114-A3	64.0	63.2	19.9	140	16.3
052114-B1	64.0	63.2	12.5	154	19.2
052114-B2	64.0	63.2	14.7	111	19.2
052114-B3	64.0	63.2	29.1	129	7.2
062514-D1	64.0	63.9	26.6	138	21.2
062514-C2	64.0	63.5	29.0	154	51.6
062514-C3	64.0	54.0	24.5	142	49.3

Table 4.5 128 g Dry Dust Results. Note the thresholds are 200 kPa and 150 kPa ms^{-1} for the peak pressure and rate of pressure increase, respectively

Dry Dust 128 g Sample Configuration					
Trial Number	Initial Weight (g)	Weight prior to test (g)	Weight posttest (g)	Peak Pressure (kPa)	Rate of Pressure Increase (kPa m s^-1)
042514-07	128	128	118	155	64.1
042514-08	128	128	118	112	21.3
042514-09	128	128	119	154	64.1
042514-10	128	128	120	154	59.4
042514-11	128	128	116	154	61.4
042514-12	128	128	125	133	24.0
052114-C1	128	127	35	138	7.1
052114-C2	128	127	38	144	15.9
052114-C3	128	127	21	134	7.3
052114-D1	128	127	29	144	41.9
052114-D2	128	127	26	133	23.4
052114-D3	128	127	65	140	44.6

4.4 Typical Wet Dust

Typical wet dust applications were also tested in this research. The wet dust samples were prepared using the industry standard 2:1 rock dust to water weight ratio. The two sample configurations resulted in marked differences in the results of the experiment. In all trials for wet dust, the weight of sample that remained on the tray was greater when compared to typical dry dust trials (i.e. the amount dispersed was less than that of dry dust experiments). These results were expected as industry applications of wet dust also indicate that the caking phenomenon prevents the rock dust from lifting and liberating from applied areas. Tables 4.6 and 4.7 summarize the experimental trials for both sample concentrations of typical wet dust applications. Each table includes the pre and post-test sample weight. The relevant pressure and pressure rise for each sample is also included to easily identify trials where a sample may have failed to stop the flame front.

Table 4.6 64g Wet dust sample results. Note the thresholds are 200 kPa and 150 kPa ms^{-1} for the peak pressure and rate of pressure increase, respectively.

Wet Dust Trials 64 g Sample Configuration					
Trial Number	Initial Weight (g)	Weight prior to test (g)	Weight posttest (g)	Peak Pressure (kPa)	Rate of Pressure Increase (kPa m s^-1)
052114-E1	96.0	62.0	55.6	150	20.1
052114-E2	96.0	62.8	56.8	112	7.1
052114-E3	96.0	68.1	61.4	162	24.1
062414-A1	96.0	56.0	37.3	134	21.6
062414-A2	96.0	49.6	46.2	147	21.1
062414-A3	96.0	40.5	19.6	136	20.2
062414-F1	96.0	75.0	71.5	292	60.7
062414-F2	96.0	71.8	66.6	159	64.4
062514-O1	96.0	79.1	36.8	154	57.1
062514-D3	96.0	80.2	39.2	144	47.2
062514-D2	96.0	77.9	38.0	144	49.5

The smaller (16g) wet sample configuration behaved similarly to typical dry dust. Across the eleven trials that were conducted with the 16g sample size, only one trial showed signs of questionable flame quenching characteristics. Trial 062414-F1 had a peak pressure of 2.917 bar which is greater than the 2 bar requirement. However, the rate of pressure increase was only 0.607 bar m s^{-1}, which does not satisfy the second condition for significant flame propagation. There is also large amount of sample that remained on the tray after the trial was completed. Figure 4.4 displays the peak pressure and the rate of pressure increase for trial 062414_F1. The black line represents the recorded explosive pressure within the chamber, and the red line represents the volume-normalized pressure derivative.

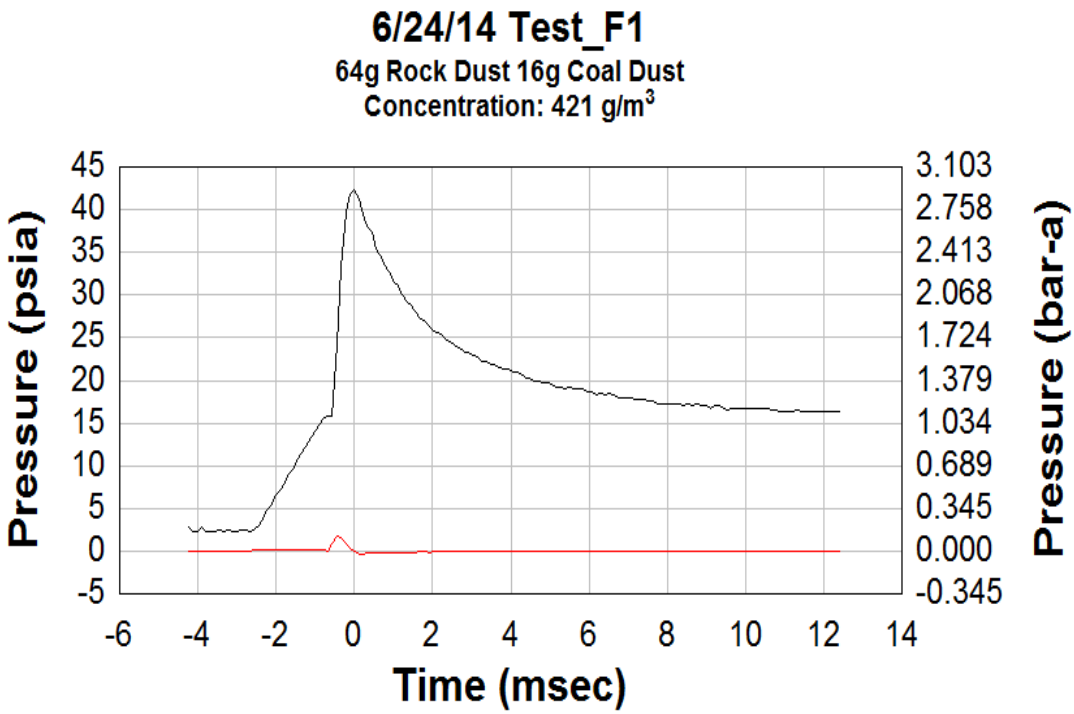

Figure 4.4 Pressure waveforms for test 062414_F1

Table 4.7 128g Wet dust sample results. Note the thresholds are 200 kPa and 150 kPa ms^{-1} for the peak pressure and rate of pressure increase, respectively.

Wet Dust Trials 128 g Sample Configuration					
Trial Number	Initial Weight (g)	Weight prior to test (g)	Weight posttest (g)	Peak Pressure (kPa)	Rate of Pressure Increase (kPa m s^-1)
052114-G1	192	131	126	357	82.8
052114-G2	192	130	125	364	25.5
052114-G3	192	129	125	583	233
062414-H3	192	179	151	112	21.5
062414-H2	192	182	164	457	378
062414-H1	192	137	139	545	533

The larger (32g coal dust) sample configuration failed to consistently stop the flame propagation after the coal dust was ignited. This suggests that the increased presence of water in the sample caused greater amount of caking which prevented the rock dust from being dispersed by the pressurized air. The smaller sample configurations also experienced caking, but not to the degree that the larger samples experienced. This increased caking is also evidenced by the weight of the sample that remained on the sample tray after the experiment was complete. Figure 4.5 compares the peak pressures between the two sample configurations. It is clearly evident that the larger samples experience significantly larger peak pressures, indicating significant caking.

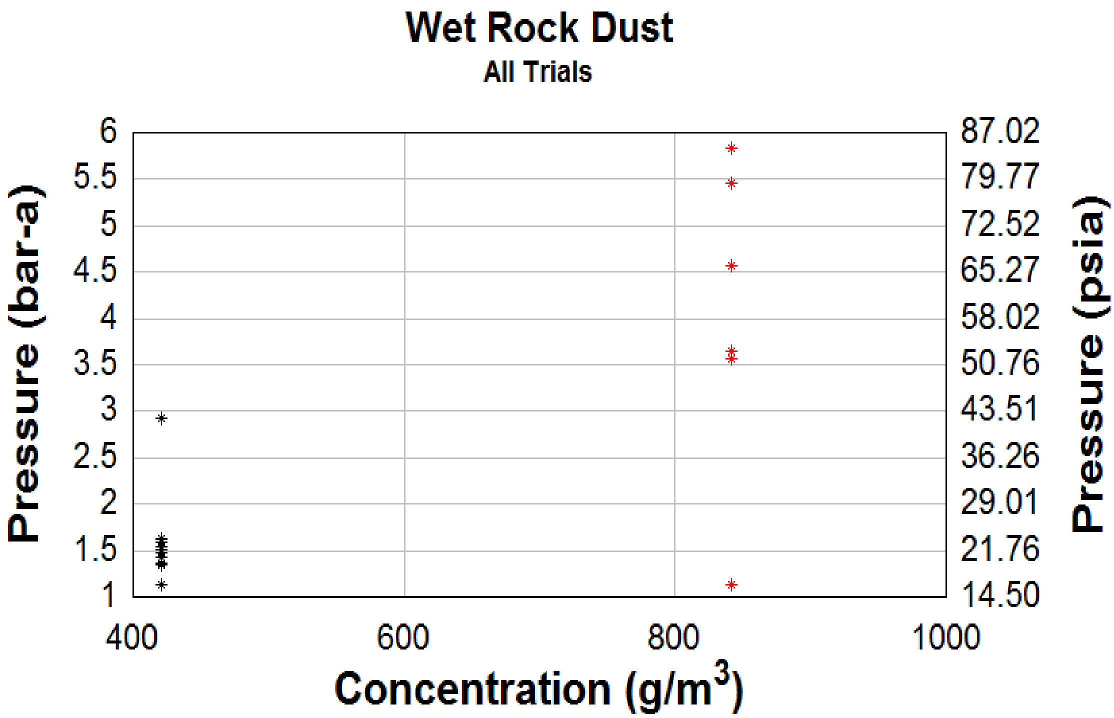

Figure 4.5 Peak pressure for wet dust trials

The dispersion of the mixture between the two sample sizes is more noticeable for the wet dust trials. The overall dispersion was 38.8%, which is significantly lower than the 57.7% dispersion that was characteristic of a dry dust trial. When examining the difference between the two sample configurations, the difference becomes even more apparent. The small sample size again had higher mixture dispersion than the larger sample size, but was lower than that of dry dust. The average mixture dispersion for the smaller sample size was 45.2%, and the value for the larger sample size was 26%. This clearly shows that the process of caking is beginning to occur for the larger sample size. The pressure values that were recorded from these trials also support this conclusion.

4.5 Hydrophobic Dust

Hydrophobic dust developed by Dr. Rick Honaker from the University of Kentucky was the third rock dust type tested. These samples were prepared in the same manner as typical wet dust samples. The sodium oleate chemical was mixed with the water prior to being combined with the rock dust. The hydrophobic dust results show improved results over the typical wet dust applications. Tables 4.8, 4.9 and Figure 4.6 show the results of the hydrophobic dust testing for both sample configurations. The peak pressure results show a slight increase between the smaller and larger samples. However, there appear to be two possible outliers within the data for the larger sample size which could have an effect on the data set. Apart from these two points, the peak pressures are clustered which indicates precision. The standard deviation of the peak pressures was determined 1.01bar-a.

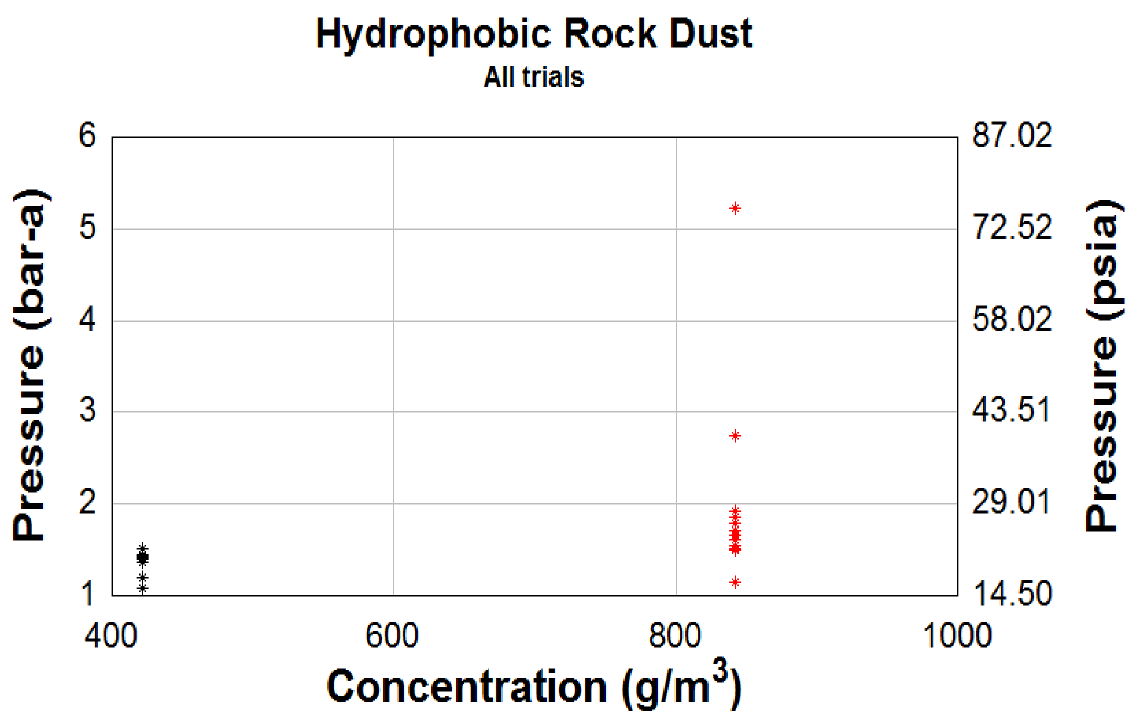

Figure 4.6 Peak pressure for hydrophobic dust trials

Table 4.8 64g Hydrophobic dust sample configuration results. Note the thresholds are 200 kPa and 150 kPa ms^{-1} for the peak pressure and rate of pressure increase, respectively.

Hydrophobic Dust Trials 64 g Sample Configuration					
Trial Number	Initial Weight (g)	Weight prior to test (g)	Weight posttest (g)	Peak Pressure (kPa)	Rate of Pressure Increase (kPa m s^-1)
062414-C1	96.0	65.2	26.8	140	21.5
062414-B3	96.0	55.3	29.7	119	21.7
062414-B2	96.0	64.6	41.6	136	21.5
062514-O2	96.0	76.8	39.0	145	51.1
062514-P1	96.0	81.4	41.0	144	49.7
062514-O3	96.0	78.9	36.9	140	21.0
071014-A1	96.0	64.4	39.5	142	46.7
071014-A2	96.0	65.4	40.5	150	61.9
071014-A3	96.0	64.9	37.8	140	21.7
071014-B2	96.0	63.0	40.3	144	49.3
071014-B3	96.0	61.5	38.5	119	21.5
071014-C1	96.0	61.2	38.9	109	21.6

Throughout all twelve trials that were conducted with the smaller sample configuration, there were no indications of significant flame propagation. The highest peak pressure, and the highest rate of pressure increase was recorded on trial 071014-A2. The peak pressure was 1.503bar, and the rate of pressure increase was 0.619 $bar\ m\ s^{-1}$. The results from these hydrophobic trials show more favorable results when compared to the same sample size typical wet dust trials. Posttest weights indicate that more rock dust was dispersed prior to the detonation of the float coal dust. Peak pressure and pressure rate values are also lower which indicates that the hydrophobic dust was able to quench the flame front more effectively than the typical wet dust samples.

Table 4.9 128g Hydrophobic dust sample configuration results. Note the thresholds are 200 kPa and 150 kPa ms^{-1} for the peak pressure and rate of pressure increase, respectively.

Hydrophobic Dust Trials 128 g Sample Configuration					
Trial Number	Initial Weight (g)	Weight prior to test (g)	Weight posttest (g)	Peak Pressure (kPa)	Rate of Pressure Increase (kPa m s^-1)
062414-K2	192	148	127	154	22.7
062414-K3	192	146	132	522	489
030215-E3	192	136	118	180	21.5
030215-E2	192	133	117	192	22.7
030215-K3	192	126	112	149	24.3
030215-G2	192	130	114	149	21.7
030215-G1	192	128	103	154	20.4
030215-F1	192	126	111	185	97.7
030215-E1	192	131	111	114	21.8
030215-I2	192	126	111	274	49.4
030215-H1	192	129	113	160	75.2
030215-G3	192	129	117	171	94.8
030215-H3	192	137	123	150	23.6
030215-F2	192	142	125	165	78.9

The data obtained from the larger samples of the hydrophobic dust indicate that the chemical additives reduce the amount of caking present when compared to typical wet dust trials; however, there were still two (2) recorded failures among the fourteen (14) trials that were conducted for the hydrophobic dust. Trial 062414-K3 exceed both threshold criteria for significant flame propagation, with a peak pressure of 5.224bar, and a rate of pressure increase of 4.893 bar m s^{-1}. However, when compared to the larger sample trials of typical wet dust, the posttest weights indicate that a larger amount of rock dust was dispersed by the pressurized air.

Mixture dispersion for the hydrophobic dust is greater than that of wet dust, and only slightly less than dry dust. The overall dispersion percentage was calculated to be 45.7%. When comparing the two sample sizes, the small sample had an average dispersion of 63.3%, and the larger sample had a dispersion of 30.5%. Results from these tests show that while the addition of the chemical additives has the potential to alleviate the problems associated with wet dust caking, further testing is needed in order to optimize the amount of chemical required to minimize the effects of caking. Figure 4.7 displays a graph of the pressure and pressure rate for trial 062414-K3.

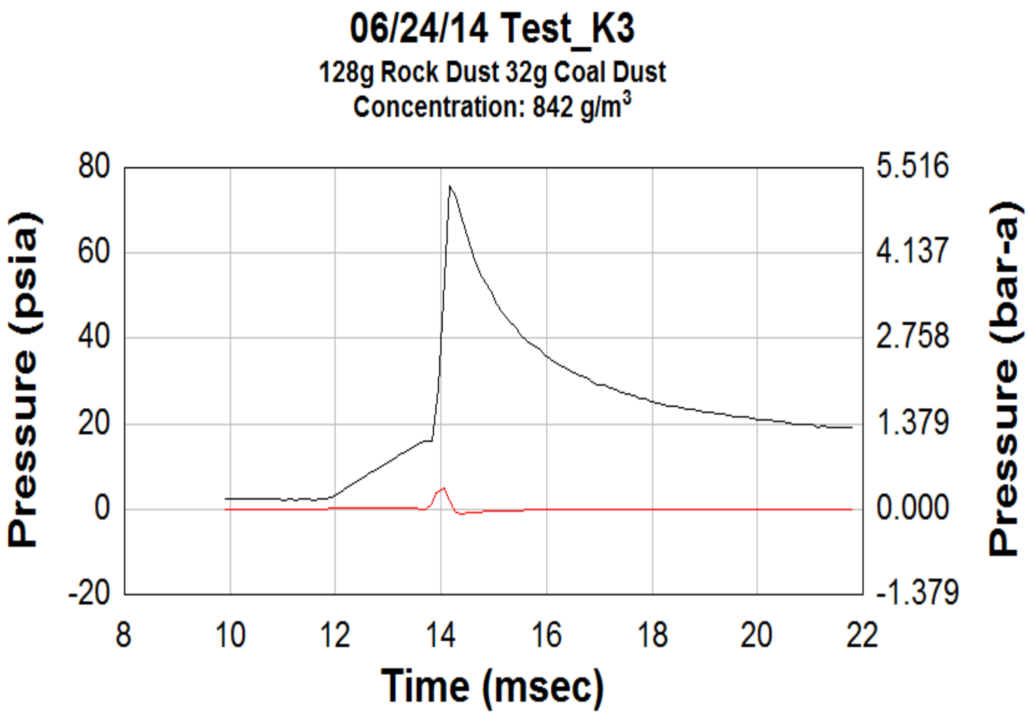

Figure 4.7 Pressure waveform for test 062414_K3

4.6 Strata FoamDust

Strata FoamDust is a recently developed product by Strata Worldwide. Through the use of chemical additives that are mixed with the water and rock dust mixture, the rock dust is polymerized. This allows the rock dust to be applied in the same manner that typical wet dust applications but allows the dust to disperse into the entry and dry/cure similarly to dry dust. This approach combines the benefits of both typical applications while remedying some of the disadvantages associated with each of the typical applications. Samples of the FoamDust were prepared by the Explosives Research Team at the University of Kentucky utilizing preparation materials that were provided by Strata. In total, seven (7) trials of FoamDust were tested in this research. Figure 4.8 compares the peak pressures that were measured between the two sample sizes. The larger samples experienced a higher peak pressure which is expected. There is also a wider range of possible pressure values for the larger sample configuration.

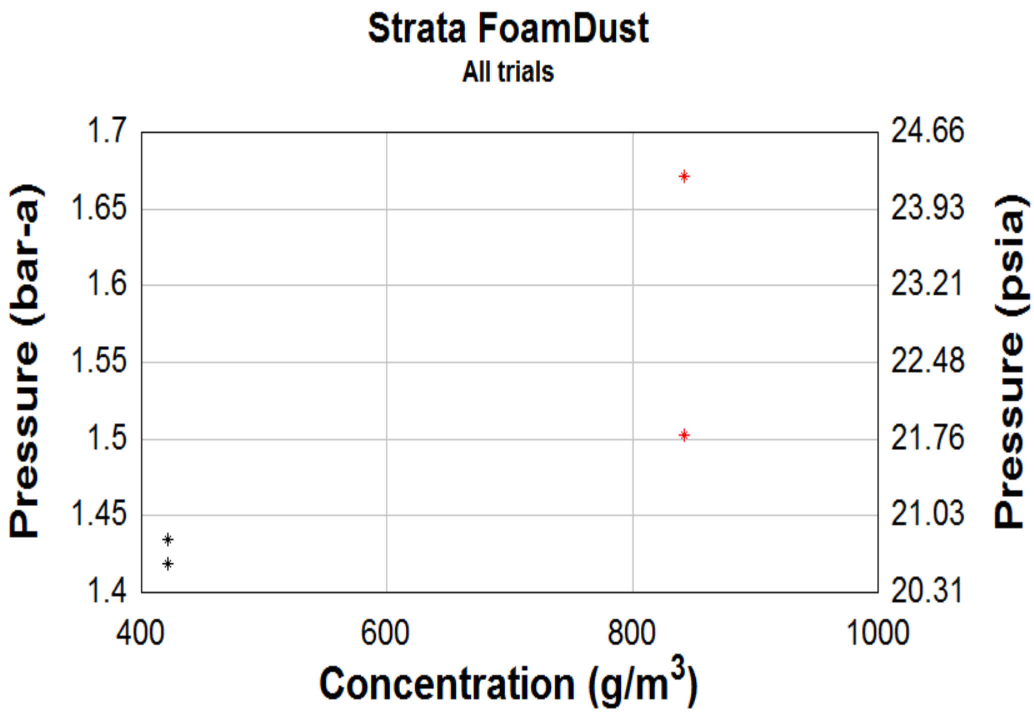

Figure 4.8 Peak pressure for strata FoamDust trials

Based on the pressure measurements that are provided in Table 4.10, it is evident that the FoamDust product has successfully prevented significant flame front propagation. The maximum pressure that was recorded in the chamber was 1.671 bar, and similarly the maximum rate of pressure increase was 0.903 bar m s^{-1}. Mixture dispersion for the FoamDust product was similar to the dispersion characteristics of the wet dust. The average mixture dispersion for the seven (7) tests that were performed was determined to be 33%. This is the lowest amount of dispersion of any of the dust types that were tested during this research. When comparing the results of mixture dispersion between the two sample sizes, the results are similar. For the small sample size, the average dispersion was 37.4 %, and for the larger sample size the dispersion was found to be 29.8%. Figure 4.9 shows the results of trial 103114-F2 which had the highest recorded peak pressure, and rate of pressure increase.

Table 4.10 Strata FoamDust sample results. Note the thresholds are 200 kPa and 150 kPa ms^{-1} for the peak pressure and rate of pressure increase, respectively.

Strata FoamDust Trials Configuration					
Trial Number	Initial Weight (g)	Weight prior to test (g)	Weight posttest (g)	Peak Pressure (kPa)	Rate of Pressure Increase (kPa ms^-1)
103114-H1	64.0	61.4	48.9	144	58.8
103114-H2	64.0	60.4	46.6	144	55.5
103114-H3	64.0	60.0	48.3	142	55.5
103114-K3	128	126	110	167	20.3
103114-F1	128	124	108	150	66.7
103114-F2	128	125	112	167	90.3
103114-K2	128	125	111	150	66.7

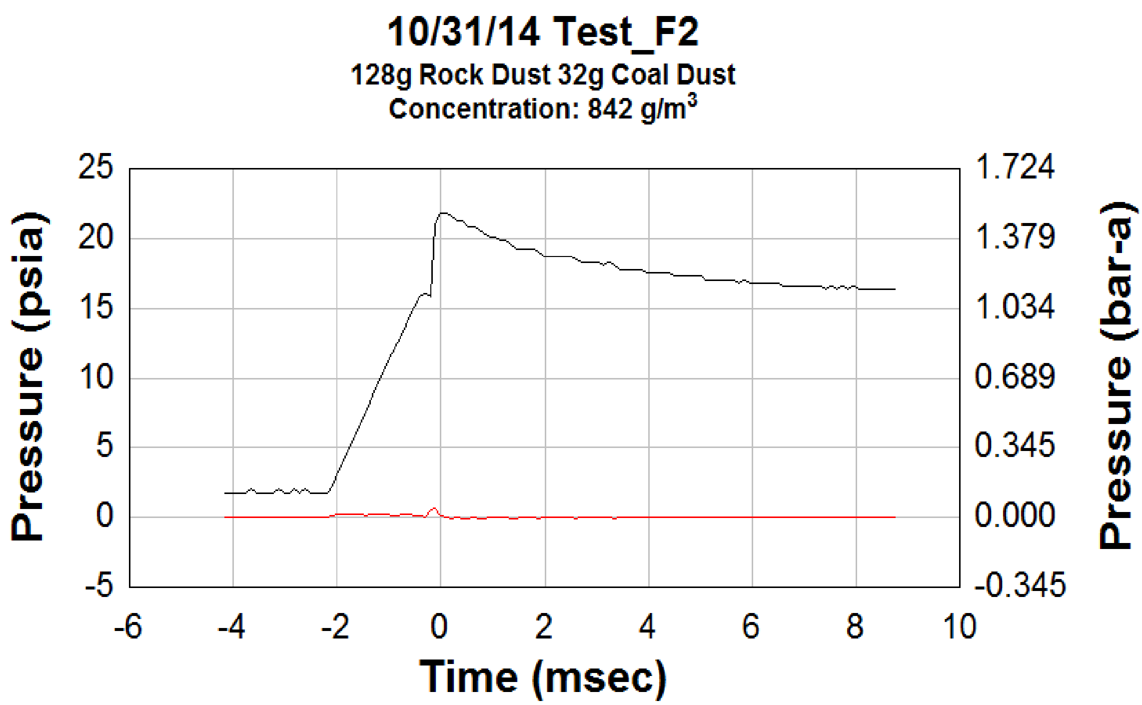

Figure 4.9 Pressure waveform for Test 103114_F2

4.7 DSI DYWI Dust

Dywidag Systems International (DSI) DYWI dust is another polymerized rock dust that attempts to combine the benefits of both dry and wet dusting. These samples were prepared by DSI and then transported to the University of Kentucky where they were allowed to cure for a period of fourteen (14) days. The samples were then transported to the testing facility. In total, twelve (12) trials of the DYWI dust were successfully conducted. Figure 4.10 shows the various peak pressures that were measured for the DSI DYWI dust. The maximum explosive pressure was approximately 150 kPa (1.5 bar), and the average explosive pressure was approximately 142 kPa (1.42 bar).

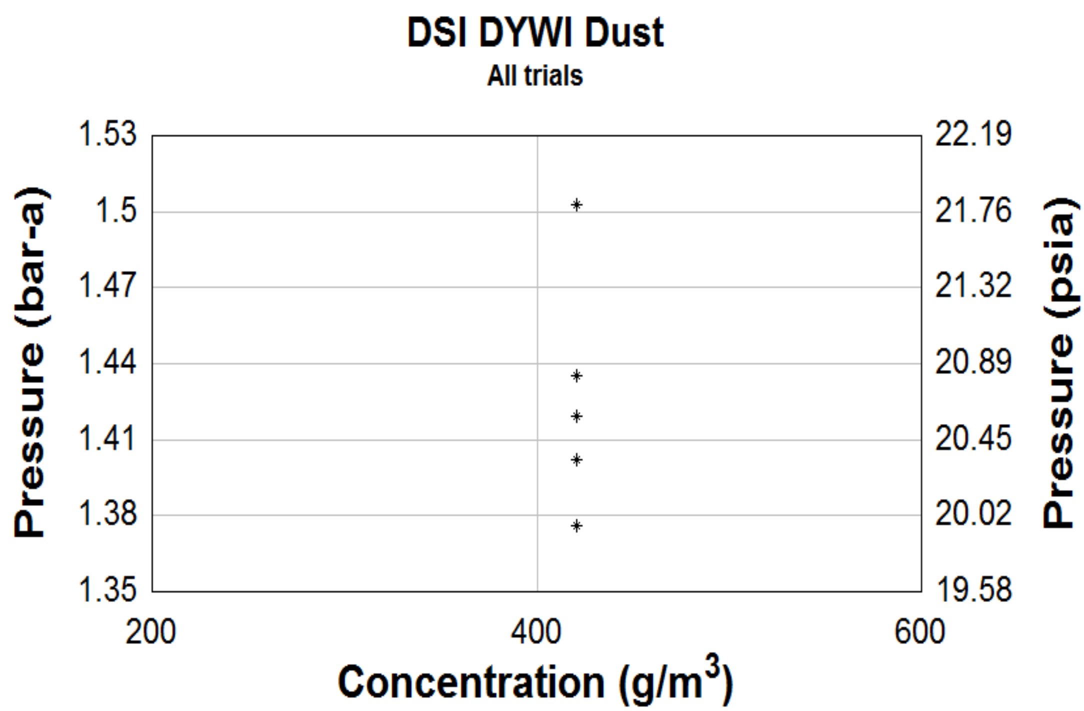

Figure 4.10 Peak pressure for DSI DYWI dust

Because the samples were prepared by DSI, only one testing configuration was tested. Table 4.11 displays the results of the DYWI dust testing. No failures were recorded from the DSI DYWI dust trials. The samples all show consistent pressure readings with many experimental trials producing identical peak explosive pressure readings.

Table 4.11 DSI DYWI sample results. Note the thresholds are 200 kPa and 150 kPa ms^{-1} for the peak pressure and rate of pressure increase, respectively.

DSI DYWI Dust Trials Configuration					
Trial Number	Initial Weight (g)	Weight prior to test (g)	Weight posttest (g)	Peak Pressure (kPa)	Rate of Pressure Increase (kPa ms^-1)
101714-E1	82.4	82.4	59.6	150	54.3
101714-G2	77.3	77.3	57.8	150	54.1
101714-I1	77.0	77.0	49.6	144	49.5
101714-E2	64.1	64.1	43.3	140	43.6
101714-E3	62.3	62.3	41.4	144	54.8
101714-G1	60.6	60.6	38.7	140	44.8
101714-G3	61.8	61.8	45.6	138	40.3
101714-I2	63.9	63.9	39.1	138	39.9
101714-21B-1	65.9	65.9	45.0	138	42.8
101714-31B	48.9	48.9	28.5	150	57.6
101714-21B-2	62.4	62.4	39.8	142	52.0
101714-21B-3	63.7	63.7	37.3	138	42.8

Based upon the above results of the DYWI testing, it is evident that the polymerized dust has prevented significant flame propagation from a coal dust explosion. Trial 101714-31B, from Table 4.10, shows the worst performance of all DYWI dust trials, but is still within the acceptable levels for pressure rise and peak pressure. The peak pressure achieved during the test was 150 kPa (1.50 bar), and the rate of pressure increase was 57.6 kPa m s^{-1} (0.576 bar m s^{-1}). However, when comparing the results of this trial to the others, it is evident that the difference between the results is not significant. When examining all trials of the DYWI dust the average percentage of mixture that was dispersed into the chamber was 47.4%. Further comparison between sample sizes shows similar results. The small sample size had an average dispersion value of 48.7%, larger samples had a similar value of 43.6%. Figure 4.11 displays a graphical representation of the pressure and rate of pressure change for trial 101714-31B.

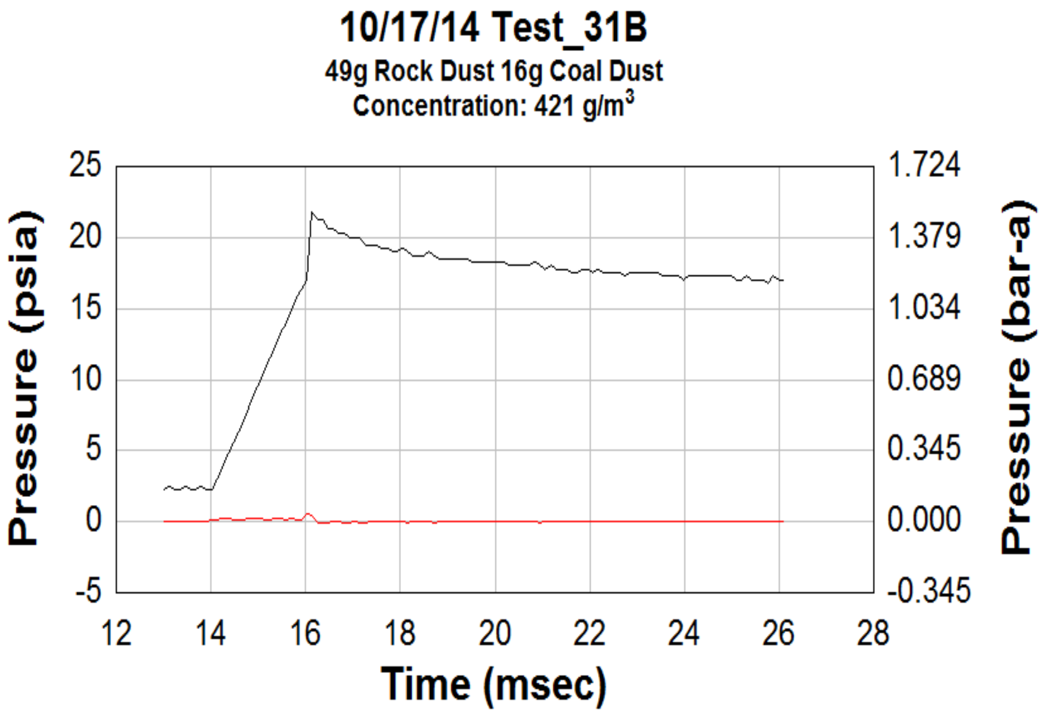

Figure 4.11 Pressure waveform for test 101714_31B

CHAPTER 5 ANGLE OF EJECTION EXPERIMENTAL SETUP

5.1 Angle of Ejection Test Method

To comprehensively compare the flame quenching characteristics of the rock dust samples, the angle of ejection for each dust type must be measured. The angle of ejection is defined as the angle from horizontal that the rock dust will liberate from the passageways after being subjected to a blast wave and subsequent impulse. To test the angle of ejection, the shock tube at the University of Kentucky Explosive Research Team facility in Georgetown, KY was used. During these tests, very large samples were used. The mean weight of the samples is 2,868g or approximately 6.3lbs. This sample size was selected because it is more representative of the condition and amounts that are common in industry applications. Samples were prepared in the same manner as the smaller samples. The curing time was increased to a minimum of fourteen (14) days to ensure that the samples had sufficient time to properly cure. Figure 5.1 shows the experimental setup that was used to measure the angle of ejection and the lift velocity of the samples.

Figure 5.1 Angle of ejection experimental setup

To measure the angle of ejection and the lift velocity of the rock dust, a velocity screen was constructed. This velocity screen consisted of a wood frame with plywood strips that intersect at one foot intervals. A high speed camera was the primary tool used to capture the ejection of the dust from the tray. Two free field pressure sensors were installed fifteen (15) inches to the side the tray and fifteen (15) inches above the tray. These sensors were placed twenty-four (24) inches apart. These sensors recorded the pressure and speed of the blast wave and activated the high speed camera. The high speed camera was placed fifteen (15) feet from the test location. The camera recorded from an angle parallel to the shock front at a lens height at the level of the tray. The camera was set to record at a rate of 250 frames per second. 1.25lb of C4 explosive was used to model a mine explosion. A single detonation was used in the trials. Preliminary testing with multiple ignitions was determined to have little effect on the behavior of the rock dust. The explosive charge was placed forty-six feet and ten inches (46'10") from the front edge of the sample tray. Figures 5.2-5.4 show the steps that were taken for each test trial.

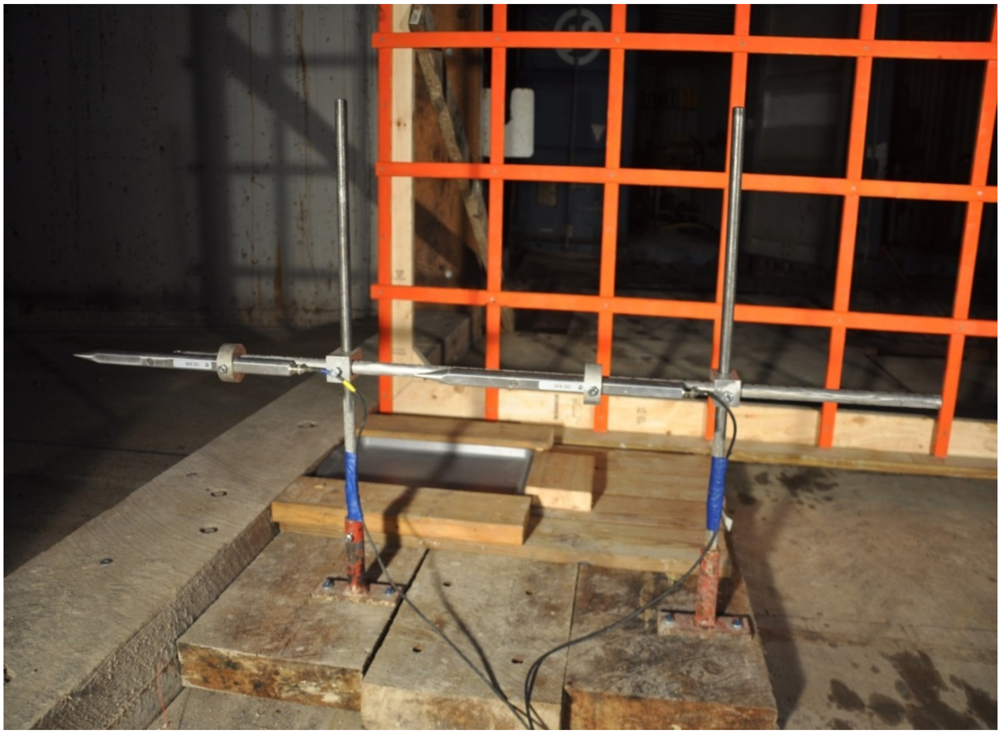

Figure 5.2 Free field pressure sensor locations

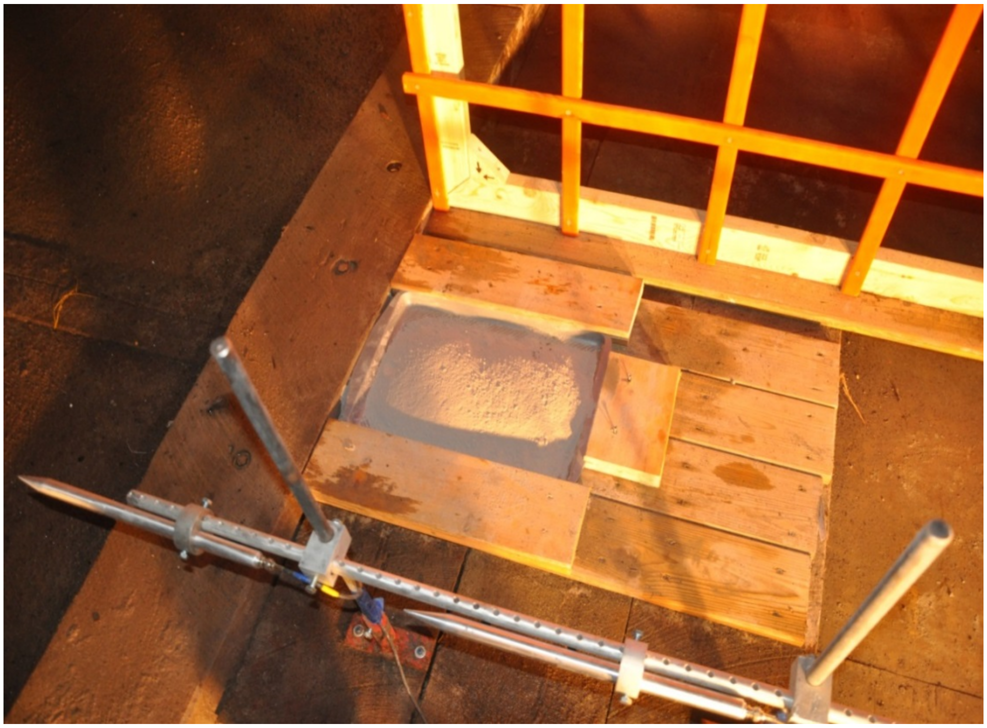

Figure 5.3 Large rock dust sample installed

Figure 5.4 Explosive charge installed in shock tube

After the test was completed, the sample tray was removed and the weight was recorded. Testing then continued by repeating the above process. In total, sixteen (16) angle of ejection samples were conducted. After returning to the laboratory at the University of Kentucky, the large samples are placed in an environmental chamber for a seven (7) day period. During this time the chamber is set to forty (40) degree Celsius or 104 degree Fahrenheit. This is done to remove any excess water that may have been present in the sample during testing. After this seven day period, the sample's weight was again recorded to determine if excess water was present during the test.

To calculate the angle of ejection and the lift velocity, the high speed video was analyzed on a frame-by-frame basis. The velocity screen created reference points to measure the distance that the dust travels after the blast wave has passed over the sample. Using these distances and trigonometry, the angle of ejection and the lift velocity were determined.

5.2 Angle of Ejection Tests

In total, sixteen (16) angle of ejection tests were conducted. A summary of the configurations for each trial is shown in Table 5.1.

Table 5.1 Summary of angle of ejection testing. (Note: One wet dust sample was destroyed in transportation)

Rock Dust Type	Trials
Dry	3
Wet	2
Hydrophobic	3
FoamDust	3
DYWI Dust	5
Total	16

CHAPTER 6 ANGLE OF EJECTION RESULTS

6.1 Typical Dry Dust Angle of Ejection

The team began with dry dust sample testing. The results from the testing verified that the dry dust has excellent ejection angle and lift velocity. The dry dust samples that were used in this testing were prepared on site, and therefore, the initial weight and the pretest weights are the same value. The samples were also not taken back to the University of Kentucky for the posttest curing period. The amount of water absorbed during the time to prepare and test the sample was negligible. Table 6.1 shows the results of the dry dust testing.

Table 6.1 Dry dust angle of ejection results

Dry Dust Angle of Ejection Results				
Trial Number	Initial Weight (g)	Posttest Weight (g)	Angle of Ejection (deg)	Lift Velocity (ft/sec)
061614-02	2867	2804	14.0	6.9
061614-03	2867	2806	23.0	7.7
061614-04_2	2867	2852	22.6	5.9
Average	2867	2820	19.9	6.8

The best results from the dry dust testing came from trial number 061614-03. Both the angle of ejection and the lift velocity were the maximum recorded values for this section of the testing. These values were twenty-three (23) degrees, and 7.7 ft/sec, respectively. The average results from the dry dust show an angle of approximately twenty (20) degrees, with a velocity of 6.8 ft/sec. Figure 6.1 shows a screen capture from the high speed camera for this particular trial.

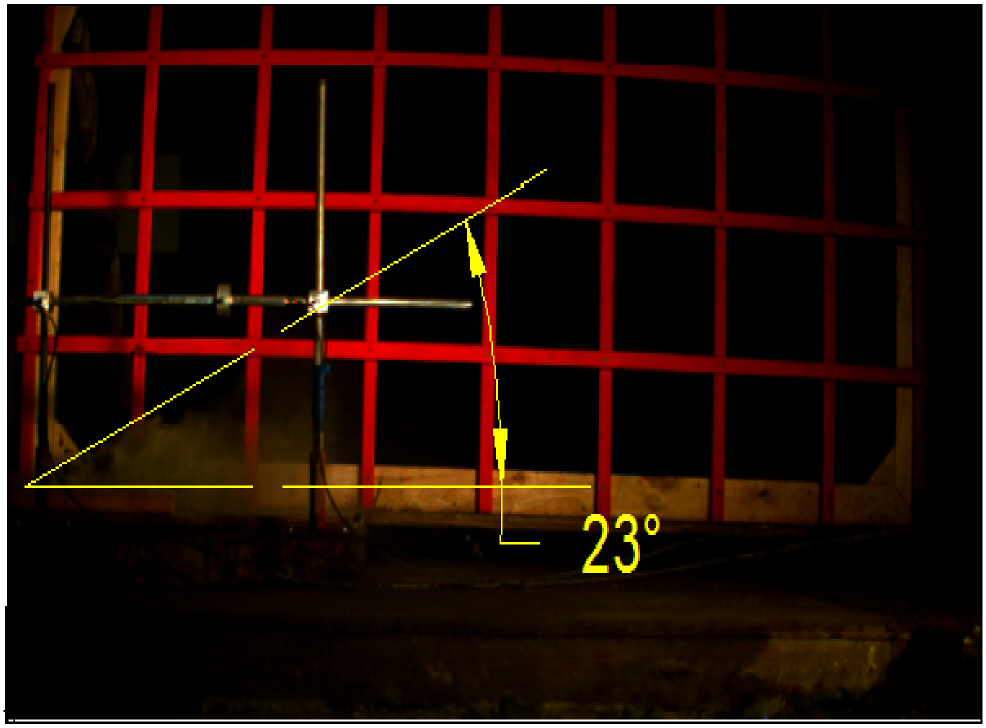

Figure 6.1 Trial 061614-03 Angle of Ejection

6.2 Typical Wet Dust Angle of Ejection

Typical wet dust samples were the second sample type that was tested. Due to the amount of water that was absorbed into the samples, the effects of caking were more pronounced with these large sample sizes than with the inerting test samples. The wet dust had lower lift velocity when compared to the typical dry dust samples. In one case, after the posttest curing period, the weight of the samples had decreased. This shows that given a minimum of fourteen (14) days for the sample to cure before the test was administered was insufficient for the excess water to be removed from the sample. This indicates that water was locked in to the material causing caking effects. Table 6.2 summarizes the results of the wet dust trials. The average values for the two trials show an angle of ejection of approximately twenty (20) degrees with a lift velocity of 4.3 ft/sec.

Table 6.2 Wet dust angle of ejection results

Wet Dust Angle of Ejection Results					
Trial Number	Initial Weight (g)	Posttest Weight (g)	Post-Curing Weight (g)	Angle of Ejection (deg)	Lift Velocity (ft/sec)
061814_03	3192	2887	2770	14.0	2.9
061814_04	3179	2690	2670	26.6	5.7
Average	3186	2788	2730	20.3	4.3

Figure 6.2 is a screen capture from the high speed camera during trial 061814_03. This case had the lowest angle of ejection and the lowest lift velocity for wet dust. This trial still had excess water during the trial. This can be seen by the difference between the posttest weight and the post-curing weight. The excess water present within the rock dust is due to the variations in the temperature and humidity of the curing location. The water present within the sample is the primary reason for the lower angle of ejection and lower lift velocity for this particular sample. This suggests that the use of wet dusting in historically “wet” mines would not be advantageous.

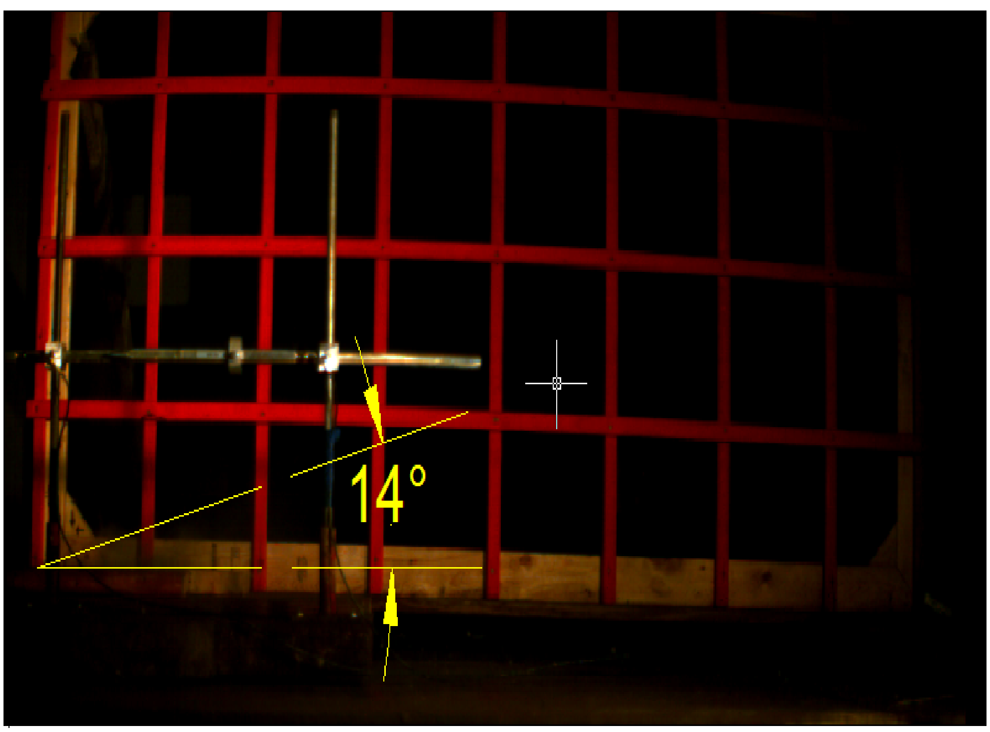

Figure 6.2 Trial 061814_03 angle of ejection

6.3 Hydrophobic Dust Angle of Ejection

The hydrophobic dust had a more consistent result. The posttest weight indicates that more rock dust sample was dispersed from the sample tray following the blast wave. The average amount of rock dust dispersed during these trials was 631g which is higher than the average values of both the wet dust and the dry dust trials. This result shows that the caking effect from the water is mitigated by the chemicals introduced during the mixing process. The angle of ejection for the three tests performed is similar to the results from the typical dry dust trials. However, the lift velocity of the hydrophobic dust is much slower than the dry dust with the results being similar to the lift velocity that was calculated from the typical wet dust trials. Table 6.3 summarizes the results of the hydrophobic dust test trials. The hydrophobic dust exhibits a higher angle of ejection than either the typical dry or typical wet dust applications. The average angle of ejection for the three trials was approximately twenty-two (22) degrees, and the average lift velocity was 3.1 ft/sec.

Table 6.3 Hydrophobic dust angle of ejection results

Hydrophobic Dust Angle of Ejection Results					
Trial Number	Initial Weight (g)	Posttest Weight (g)	Post-Curing Weight (g)	Angle of Ejection (deg)	Lift Velocity (ft/sec)
061814_01	3507	2766	2766	26.6	3.2
061814_02	3532	2926	2926	20.6	2.0
070814_01	3546	3000	3000	18.4	4.2
Average	3529	2897	2897	21.9	3.1

Figure 6.3 shows a screen capture of trial 0708_01 from the hydrophobic test trials. This test trial has the lowest angle of ejection among the hydrophobic tests, however, it has the highest lift velocity, and the lowest amount of sample liberation. In all cases, the hydrophobic samples had cured for a sufficient time period to allow all the excess water to evaporate from the sample. The post-curing weights after testing was completed verified this result.

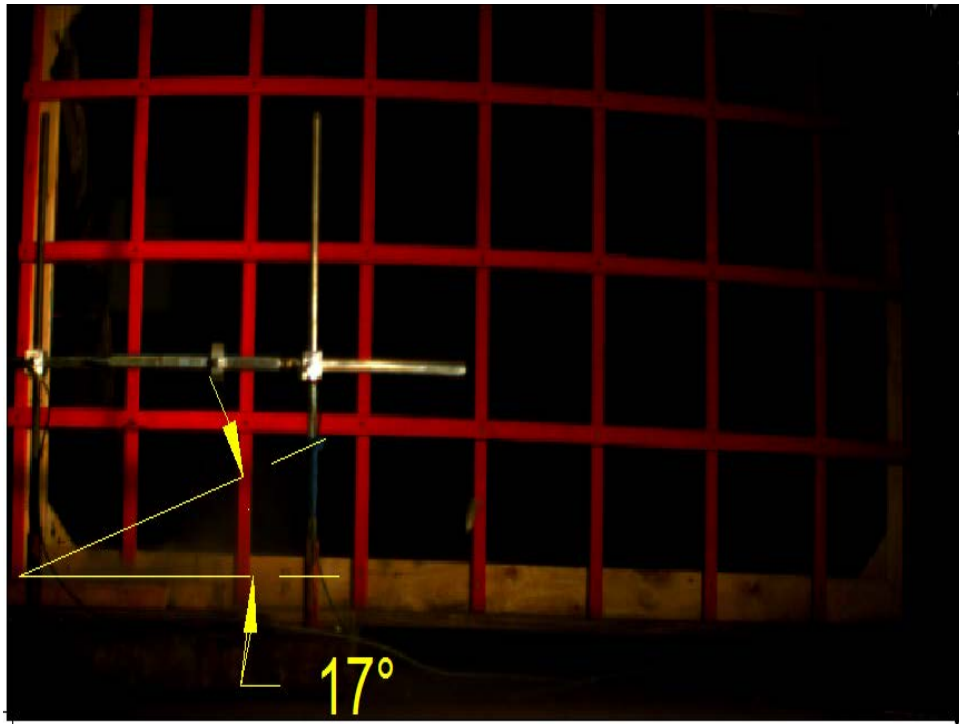

Figure 6.3 Trial 0708_01 angle of ejection

6.4 Strata FoamDust Angle of Ejection

The Strata FoamDust results show great promise. The angle of ejection from the three trials conducted is the highest recorded from all rock dust types. The recorded lift velocities are also similar to the results of dry dust trials. However, trial 070814_02 has the lowest recorded lift velocity. The FoamDust also had the largest amount of sample liberated after the blast wave had passed over. The average amount of rock dust that was liberated from the sample tray was 920 grams, which is approximately 25% of the sample. Table 6.4 shows the results for the FoamDust angle of ejection trials. Based on the table, the average angle of ejection for the FoamDust was forty-one (41) degrees, and an average velocity of 4.27 ft/sec.

Table 6.4 Strata FoamDust angle of ejection results

FoamDust Dust Angle of Ejection Results					
Trial Number	Initial Weight (g)	Posttest Weight (g)	Post-Curing Weight (g)	Angle of Ejection (deg)	Lift Velocity (ft/sec)
070814_02	3780	2880	2860	63.4	1.9
070814_03	3780	2880	2860	32.0	5.2
070814_04	3780	2860	2860	26.6	5.7
Average	3780	2873.33	2860	40.7	4.3

Figure 6.4 shows a screen capture of trial 070814_04 from the FoamDust trials. The angle of ejection and the lift velocity from this trial were both very similar to the results of the dry dust trials. The post-curing weight for all the FoamDust samples was the same as the posttest weight, indicating that the curing time of seven (7) days was sufficient for the excess water in the sample to evaporate under typical temperature and humidity conditions for an underground coal mine.

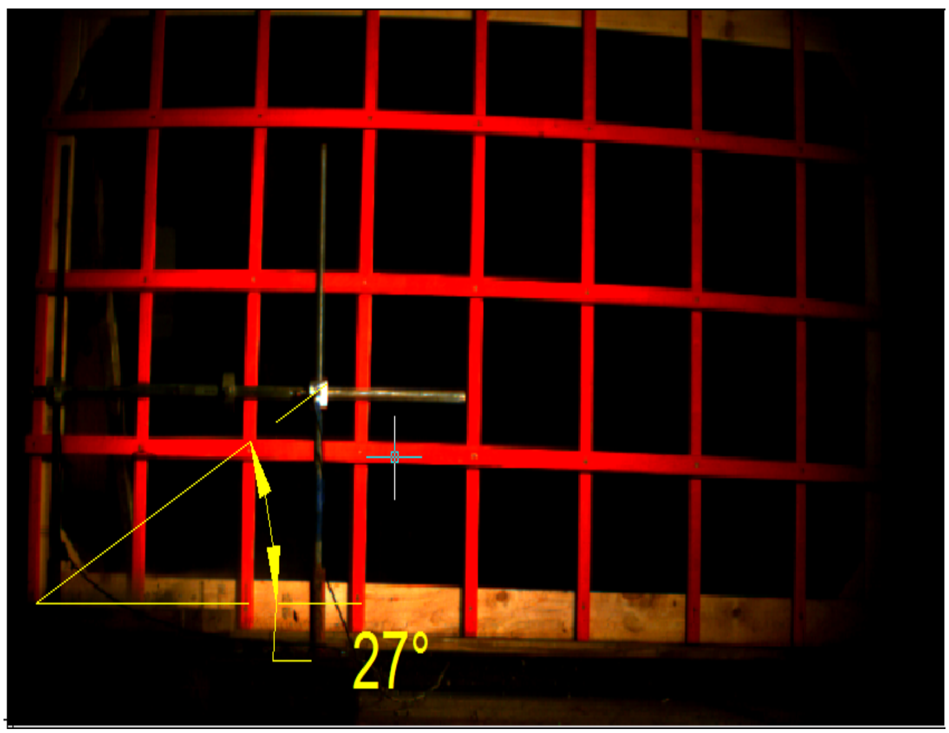

Figure 6.4 Trial 070814_04 angle of ejection

6.5 DSI DYWI Dust Angle of Ejection

DYWI dust performed similarly to other types of rock dusts that were tested in this research. The angle of ejection is significantly higher than both typical dry and wet dusts, and the lift velocities are still acceptable. However, the weight dispersion for the DYWI is the lowest among all rock dusts that were tested. The average weight dispersed during these trials was approximately 0.4%. Table 6.5 shows the values of each experimental trial and the average among all trials for the DSI DYWI dust. The average angle of ejection was approximately twenty-nine (29) degrees, and the lift velocity was 3.62 ft/sec.

Table 6.5 DSI DYWI angle of ejection results

DYWI Dust Angle of Ejection Results				
Trial	Pretest Weight (g)	Posttest Weight (g)	Angle of Ejection (degree)	Lift Velocity (ft/sec)
040115_1	1044	1041	40.0	2.8
040115_2	1025	1021	26.6	4.3
040115_3	1221	1209	18.4	4.0
040115_4	1165	1163	26.6	4.2
040115_5	1180	1178	26.6	2.9
Average	1127	1122	27.6	3.6

Figure 6.5 shows a screen capture of trial 040115_1. This trial exhibits the highest angle of ejection for the DYWI dust. The DYWI dust samples were prepared by DSI and delivered to the University for testing. Therefore, the weight dispersion is simply based on the measured weights of the sample before and after the test was completed. Due to the uncertainties associated with the sample creation process, the samples were not cured after the test to ensure that the sample was completely dried. Similarly, the pretest curing time was not taken into account when evaluating these samples.

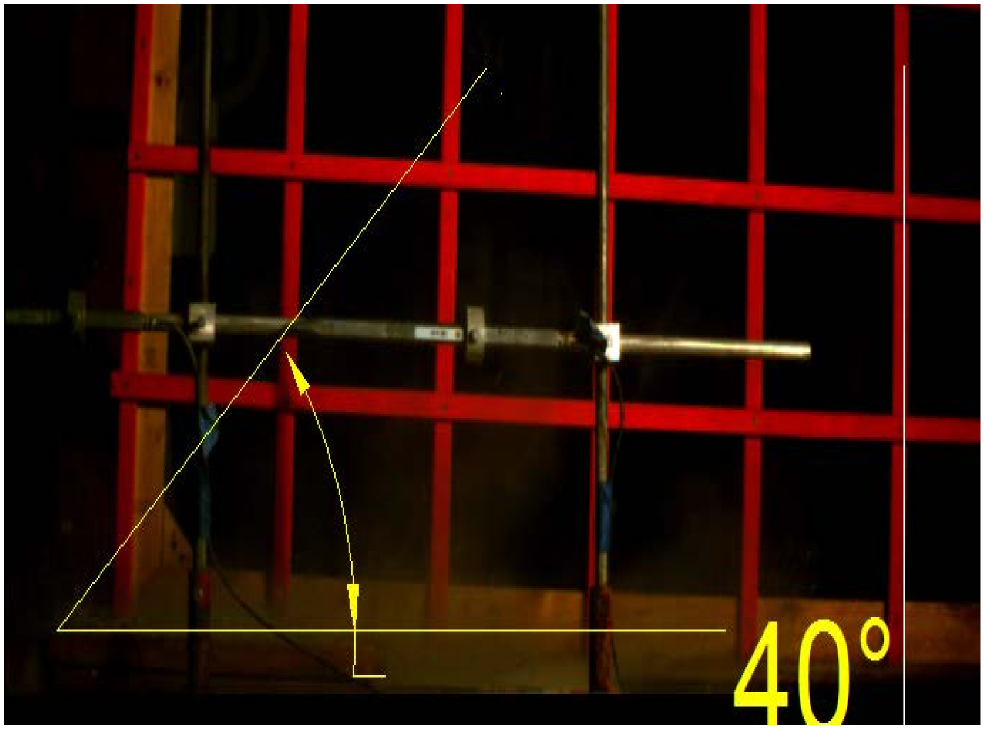

Figure 6.5 Trial 040115_01 angle of ejection

Based upon the results of the tests, the average lift angle for the DYWI dust was determined to be 27.6 degrees, with a velocity of 3.6 ft/sec. The angle of ejection is improved when compared to the dry dust and wet dusting trials, with ejection angles of 19.9 and 20.3 degrees, respectively. This indicates that caking of the rock dust particles has been reduced. The concepts of projectile motion from Newtonian physics indicate that an object of lower mass will have a higher angle when the amount of energy used to project the object remains constant. The lift velocity is slightly lower than the recorded velocities for the dry and wet dusts, however, no established criteria exist for measuring the velocity that rock dust must eject from the exposed surfaces of the entry, and the results are reasonable when compared to the results of the other rock dust types.

CHAPTER 7 COSTING ESTIMATE

7.1 Associated Costs

To completely assess these new types of rock dust, a comparative cost analysis has been conducted on a cost per raw coal ton basis. The cost comparison was made only between: dry dust, wet dust, and hydrophobic dusting. Previous economic analysis has been conducted of the DYWI dust. Results of this analysis indicate that the addition of all chemicals needed for the DYWI dust add between 0.02- 0.04 $/clean coal ton [Pinkley et al. 2012]. Figure 7.1 and Table 7.1 show the dimensions of the typical underground coal mine entry used in this cost analysis.

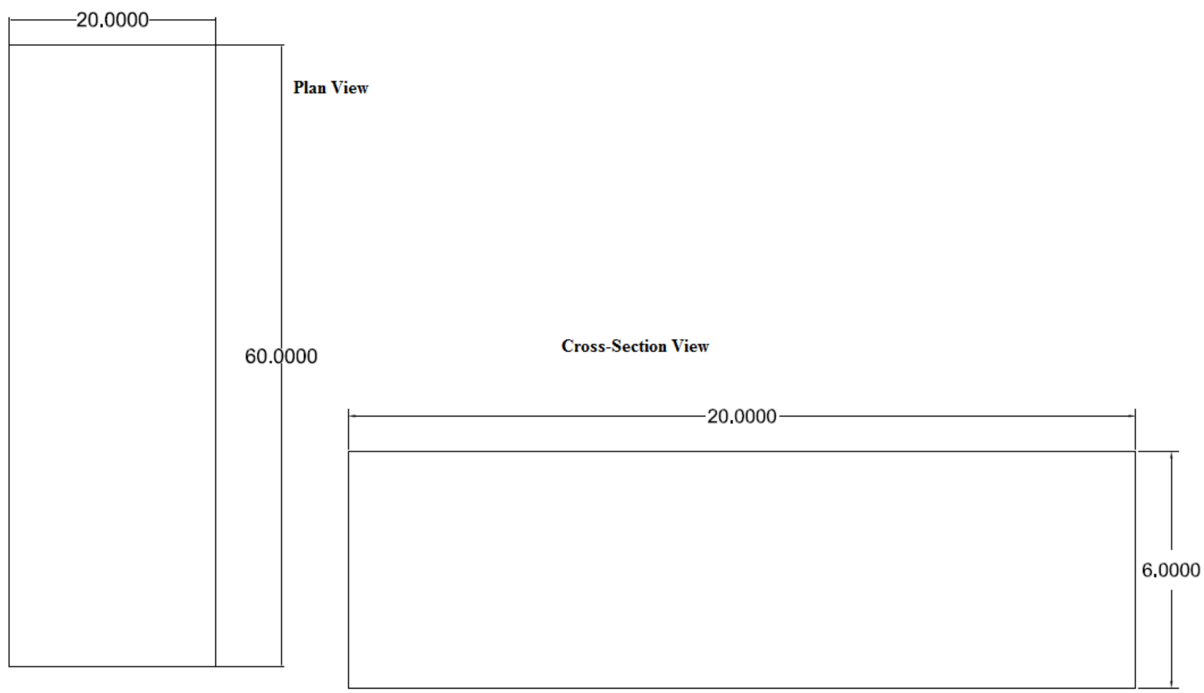

Figure 7.1 Example coal mine entry

Table 7.1 Example Entry Dimensions

Dimension	Measurement (ft)
Length	60
Width	20
Height	6

Using these dimensions and assuming an average coal density of 82 lb/ft^3, typical of eastern Kentucky coal, the raw tonnage of the coal is shown in Table 7.2. Table 7.3 shows the comparison between the three dust types for a six (6) foot mining height. The thickness of applied rock dust was varied between 0.01 in and 0.5 in.

Table 7.2 Raw coal tonnage

Width(ft)	Height (ft)	Length (ft)	Coal Density (lb/ft^3)	Coal Tonnage (ton)
20	6	60	82	295.2

Table 7.3 Dusting prices for 6ft mining height

Dust Prices ($ / raw ton)			
Thickness (in)	Dry	Wet	Hydrophobic
0.01	0.01	0.01	0.06
0.05	0.05	0.06	0.28
0.10	0.10	0.11	0.56
0.20	0.20	0.21	1.12
0.30	0.31	0.31	1.68
0.40	0.41	0.41	2.23
0.50	0.51	0.51	2.79

Further analysis was conducted with a seven (7) foot mining height, and a five (5) foot mining height. These heights were selected due to their typical mining heights for underground coal mines. They provide a sensitivity analysis of the mining height to the overall cost of rock dusting. Table 7.4 displays the rock dusting prices for the 7ft mining height, and table 7.5 shows the 5ft mining height. After inspection of the tables, it is clear that hydrophobic dusting is significantly more expensive than the traditional methods of dusting on a raw ton basis. However, materials and chemicals were purchased in small volume orders. If this type of rock dust hydrophobization gains greater acceptance, bulk orders should decrease the overall cost per ton.

Table 7.4 Dusting prices for 7ft mining height

Dust Prices ($ / raw ton)			
Thickness	Dry	Wet	Hydrophobic
0.01	0.01	0.02	0.07
0.05	0.06	0.07	0.35
0.10	0.13	0.13	0.70
0.20	0.25	0.26	1.39
0.30	0.38	0.39	2.09
0.40	0.51	0.51	2.79
0.50	0.63	0.64	3.48

Table 7.5 Dusting prices for a 5ft mining height

Dust Prices ($ / raw ton)			
Thickness	Dry	Wet	Hydrophobic
0.01	0.01	0.02	0.06
0.05	0.06	0.06	0.28
0.10	0.12	0.12	0.55
0.20	0.24	0.24	1.10
0.30	0.35	0.36	1.64
0.40	0.47	0.48	2.19
0.50	0.59	0.59	2.73

CHAPTER 8 CONCLUSIONS

8.1 Conclusions

This project was able to successfully test the flame quenching characteristics of several types of rock dust. Using the data from these tests, the team was able to compare the characteristics of these three dusts to typical industry applications. Table 8.1 shows a comparison of the results for each of the five dusts that were tested in this research.

Table 8.1 Experimental results for five rock dust types

Dust Type	Total Trials	Success	Failure	Average Angle of Ejection (deg)	Average Lift Velocity (ft/sec)
Dry	32	32	0	19.9	6.8
Wet	18	12	6	20.3	4.3
Hydrophobic	26	24	2	21.9	3.1
FoamDust	7	7	0	40.7	4.3
DYWI	12	12	0	27.7	3.6

Strata FoamDust had marginally better overall results from the two experiments. FoamDust was similar to DSI DYWI and dry dusts with zero recorded failures, however, the angle of ejection was the highest recorded, and the lift velocity is comparable to the other dusts. Dry and DYWI dusts have similar results. Typical wet dusting had the next best results, however, the number of recorded failures was the highest, which takes precedence over the other result categories. Hydrophobic performed better than wet dusting in flame quenching and angle of ejection, however, the lift velocity was the lowest recorded among the five dusts tested. All lift velocities were based on the dust being lifted from the floor; further studies are necessary to determine the characteristics of the dusts coming off of rib and roof surfaces.

Typical dry dust applications have a proven history of successful flame-quenching. The typical wet dusting trials clearly demonstrate the reason that alternative rock dust types are necessary for the coal mining industry. Among the eighteen (18) trials that were conducted, six (6) failures occurred. Further analysis shows that five (5) of those failures happened when testing the larger sample size. This indicates that the increase in water has an increase in the amount of caking that occurs within the rock dust sample. These larger sample sizes are a more accurate representation of industrial applications for wet dusting, and clearly demonstrate the ineffectiveness of typical wet dusting applications. One additional aspect that can be looked further into in future work is the thickness of the overall sample. With the larger samples, the amount of rock dust and coal dust increased but stayed at the required ratio of 80% incombustible resulting in a larger overall thickness of the sample. However, after the mixture was dispersed, it appeared that the same volume of rock dust was liberated from the tray as the smaller, or thinner, dust sample. This results in a richer coal dust mixture that is dispersed and is more likely to detonate. Different experimental setup and apparatus may be necessary to achieve this work. The angle of ejection testing results show that caking has minimal effect on the angle of ejection and lift velocity of the rock dust sample, however, after visual inspection, it is apparent that the liberated rock dust has caked into clumps, and would have diminished flame-quenching characteristics.

The three experimental alternatives to typical wet dusting applications have relatively similar results. The DYWI dust and FoamDust successfully prevented significant flame propagation for all experimental trials. The hydrophobic dust had marginally decreased performance compared to the DYWI and FoamDust. The hydrophobic product is currently undergoing optimization procedures to maximize the effectiveness of the sodium oleate additive. If the amount used in the experimental trials was sub-optimal; this could be a contributing factor to the decreased performance of the hydrophobic dust. The difference between peak explosive pressures of the two sample configurations for the three experimental dusts shows a reduction in the amount of caked rock dust. With the project complete, and all major objectives of this research achieved, these results can be used to obtain experimental approval from regulatory agencies.

APPENDIX A

Mine	Production, Mt/yr	Incombustible, %	Soluble, %	Size analysis: −270 mesh or < 53 µm, %	Size analysis: −70 mesh or < 212 µm, %	ash, %	Corrected size analysis: −270 mesh or < 53 µm, %	Corrected: −200 mesh or < 75 µm, %	Corrected: −140 mesh or < 106 µm, %	Corrected: −100 mesh or < 150 µm, %	Corrected: −70 mesh or < 212 µm, %	Corrected: −50 mesh or < 300 µm, %	Corrected: −40 mesh or < 425 µm, %	Corrected: −30 mesh or < 600 µm, %	D_{mass}, µm
1	>1	86	74	83	92	24	74	83	87	90	93	95	97	98	~30
		80	74	63	80	34	55	62	66	73	79	86	94	99	44
		87	76	72	88	41	62	69	74	79	83	88	93	98	42
2	>1	68	53	40	62	45	33	37	42	48	58	71	87	97	155
3	>1	63	40	57	72	35	44	47	52	59	66	75	85	95	91
		75	54	76	85	43	68	71	74	77	82	89	95	99	~20–25
4	<1	77	69	28	55	19	22	27	33	42	54	66	81	94	188
5	>1	82	79	85	93	12	78	84	88	90	93	95	98	99	~36
6	>1	80	75	59	76	15	52	58	63	68	75	82	90	97	49
7	>1	91	75	52	82	65	46	52	58	67	76	87	96	99	67
8	>1	72	45	63	78	43	52	57	62	68	75	82	91	98	45
9	>1	85	78	42	72	26	29	36	45	57	69	80	91	97	122
10	<1	46	14	38	83	32	24	30	40	55	79	95	99	100	135
11	>1	75	60	33	62	38	22	26	34	44	57	72	88	98	176
12	<1	37	24	27	54	18	19	24	32	42	53	66	80	93	193
13	<1	70	58	38	64	36	30	35	42	52	64	75	88	97	140
14	>1	71	75	42	68	22	30	35	43	53	63	75	87	96	137
15	>1	83	83	47	73	32	31	37	45	56	67	78	89	97	124
16	>1	76	54	41	64	49	24	27	34	42	54	68	84	96	190
17	>1	72	19	42	63	61	26	30	36	44	55	67	82	95	184
18	<1	50	29	32	56	27	24	30	37	45	55	67	82	95	178
19	<1	92	78	75	90	62	60	64	69	77	83	90	96	99	30
20	<1	89	68	36	62	60	20	25	33	43	54	68	85	97	189
21	<1	81	14	43	75	79	27	33	38	47	57	76	90	98	171
22	<1	86	62	56	75	65	32	35	43	52	61	72	84	94	141
23	>1	83	53	53	74	59	27	31	37	46	57	72	88	97	170
24	>1	64	40	38	63	132	22	29	36	45	56	69	83	95	178
25	>1	62	22	42	63	40	24	28	34	42	52	66	83	96	199
		56	22	43	65	37	25	29	35	44	55	69	87	97	182
26	>1	89	79	82	93	59	64	71	77	81	84	90	95	99	30
		70	70	47	69	28	33	40	47	56	64	75	87	96	121
27	>1	79	69	46	73	29	31	37	45	56	67	80	91	98	124
28	>1	77	74	36	60	19	23	28	35	44	53	66	81	93	189
29	<1	66	53	30	54	12	21	26	32	40	50	63	80	94	211
30	<1	61	40	35	57	34	23	28	33	41	51	64	80	94	208
		62	16	39	66	54	25	30	37	46	57	73	88	97	171
31	>1	88	81	36	62	39	20	26	35	44	51	64	79	93	201
32	<1	65	21	44	70	52	25	29	35	44	54	69	83	95	186
33	<1	96	95	81	89	60	65	71	76	80	83	88	93	98	~25–30
34	>1	94	90	58	79	36	40	46	54	62	72	82	91	97	91
		93	88	50	79	26	33	40	49	61	74	87	95	99	109
		88	82	47	66	42	27	32	38	45	54	66	80	92	183
35	>1	39	25	38	66	17	28	33	41	50	62	77	91	98	148
36	<1	41	26	26	55	16	18	23	30	39	52	69	87	97	203
				average for all MSHA Districts			35	41	47	55	65	76	88	97	132
					standard deviation		17	17	16	14	12	10	6	2	62

Figure A.1. Analyses of size of coal dust particles from return airways in 36 mines [NIOSH 2010].

APPENDIX B

Trial Number	Dust Type	Tray Type	Sample Prep Date	Sample Test Date	Cure Type	Initial Weight (g)	Weight prior to test (g)	Weight post test (g)	Coal Dust used (g)	Peak Pressure Achieved (psia)
042514-01	Dry	Deep	4/25/2014	4/25/2014	Mine	64	64	57.1	16	22.771673
042514-02	Dry	Deep	4/25/2014	4/25/2014	Mine	64	64	53	16	16.544567
042514-03	Dry	Deep	4/25/2014	4/25/2014	Mine	64	64	57.1	16	22.527473
042514-04	Dry	Deep	4/25/2014	4/25/2014	Mine	64	64	57.6	16	19.23077
042514-05	Dry	Deep	4/25/2014	4/25/2014	Mine	64	64	57.2	16	21.550672
042514-06	Dry	Deep	4/25/2014	4/25/2014	Mine	64	64	44.3	16	19.96337
042514-07	Dry	Deep	4/25/2014	4/25/2014	Mine	128	128	118.3	32	22.527473
042514-08	Dry	Deep	4/25/2014	4/25/2014	Mine	128	128	117.5	32	16.300367
042514-09	Dry	Deep	4/25/2014	4/25/2014	Mine	128	128	118.5	32	22.283272
042514-10	Dry	Deep	4/25/2014	4/25/2014	Mine	128	128	120.2	32	22.283272
042514-11	Dry	Deep	4/25/2014	4/25/2014	Mine	128	128	115.5	32	22.283272
042514-12	Dry	Deep	4/25/2014	4/25/2014	Mine	128	128	125.2	32	19.23077
052114-11	Dry	Deep	4/25/2014	5/21/2014	Mine	64	64.55	30.4	16	19.96337
052114-12	Dry	Deep	4/25/2014	5/21/2014	Mine	64	64.6	16.9	16	22.039072
052114-13	Dry	Deep	4/25/2014	5/21/2014	Mine	64	64.8	16.2	16	17.277168
052114-14	Dry	Deep	4/25/2014	5/21/2014	Mine	64	64.7	22.2	16	20.573871
052114-15	Dry	Deep	4/25/2014	5/21/2014	Mine	64	64.7	8.8	16	18.986569
052114-A1	Dry	Slim	5/2/2014	5/21/2014	Lab	64	63.04	17.67	16	19.23077
052114-A2	Dry	Slim	5/2/2014	5/21/2014	Lab	64	63.21	19.65	16	20.573871
052114-A3	Dry	Slim	5/2/2014	5/21/2014	Lab	64	63.17	19.86	16	20.329671
052114-B1	Dry	Slim	5/2/2014	5/21/2014	Lab	64	63.15	12.46	16	22.283272
052114-B2	Dry	Slim	5/2/2014	5/21/2014	Lab	64	63.18	14.69	16	16.056167

052114-B3	Dry	Slim	5/2/2014	5/21/2014	Lab	64	63.22	29.07	16	18.742369
052114-C1	Dry	Slim	5/2/2014	5/21/2014	Lab	128	127.19	34.95	32	19.96337
052114-C2	Dry	Slim	5/2/2014	5/21/2014	Lab	128	127.13	38.42	32	20.818071
052114-C3	Dry	Slim	5/2/2014	5/21/2014	Lab	128	126.68	21.25	32	19.47497
052114-D1	Dry	Slim	5/2/2014	5/21/2014	Lab	128	127.18	29.01	32	20.818071
052114-D2	Dry	Slim	5/2/2014	5/21/2014	Lab	128	127.06	25.66	32	19.23077
052114-D3	Dry	Slim	5/2/2014	5/21/2014	Lab	128	127.19	65.4	32	20.329671
052114-E1	Wet	Deep	5/2/2014	5/21/2014	Lab	96	61.94	55.62	16	21.794872
052114-E2	Wet	Deep	5/2/2014	5/21/2014	Lab	96	62.84	56.75	16	16.300367
052114-E3	Wet	Deep	5/2/2014	5/21/2014	Lab	96	68.1	61.39	16	23.504274
052114-G1	Wet	Deep	5/2/2014	5/21/2014	Lab	192	131.23	125.94	32	51.709402
052114-G2	Wet	Deep	5/2/2014	5/21/2014	Lab	192	130.37	125.16	32	52.808303
052114-G3	Wet	Deep	5/2/2014	5/21/2014	Lab	192	128.84	124.77	32	84.554332
062414-C1	Hydrophobic	Slim	5/22/2014	6/24/2014	Lab	96	65.21	26.81	16	20.329671
062414-K2	Hydrophobic	Deep	5/22/2014	6/24/2014	Lab	192	147.86	127.36	32	22.283272
062414-K3	Hydrophobic	Deep	5/22/2014	6/24/2014	Lab	192	146.15	131.85	32	75.763124
062414-B3	Hydrophobic	Slim	5/22/2014	6/24/2014	Lab	96	55.33	29.73	16	17.277168
062414-A1	Wet	Slim	5/22/2014	6/24/2014	Lab	96	55.9	37.3	16	19.47497
062414-A2	Wet	Slim	5/22/2014	6/24/2014	Lab	96	49.55	46.15	16	21.306472
062414-A3	Wet	Slim	5/22/2014	6/24/2014	Lab	96	40.47	19.57	16	19.71917
062414-B2	Hydrophobic	Slim	5/22/2014	6/24/2014	Lab	96	64.63	41.63	16	19.71917
062414-H3	Wet	Deep	5/2/2014	6/24/2014	Lab / Mine	192	178.74	150.94	32	16.300367
062414-H2	Wet	Deep	5/2/2014	6/24/2014	Lab / Mine	192	182.31	164.11	32	66.239315
062414-H1	Wet	Deep	5/2/2014	6/24/2014	Lab / Mine	192	137.23	138.83	32	79.059827
062414-F1	Wet	Deep	5/2/2014	6/24/2014	Lab / Mine	96	74.99	71.49	16	42.307693
062414-F2	Wet	Deep	5/2/2014	6/24/2014	Lab / Mine	96	71.78	66.58	16	23.015873
062514-D1	Dry	Slim	6/11/2014	6/25/2014	Chamber	64	63.87	26.57	16	19.96337
062514-O1	Wet	Slim	6/11/2014	6/25/2014	Chamber	96	79.13	36.83	16	22.283272
062514-C2	Dry	Slim	6/11/2014	6/25/2014	Chamber	64	63.48	28.98	16	22.283272
062514-O2	Hydrophobic	Slim	6/11/2014	6/25/2014	Chamber	96	76.82	39.02	16	21.062271

062514-P1	Hydrophobic	Slim	6/11/2014	6/25/2014	Chamber	96	81.35	41.05	16	20.818071
062514-C3	Dry	Slim	6/11/2014	6/25/2014	Chamber	64	53.95	24.45	16	20.573871
062514-O3	Hydrophobic	Slim	6/11/2014	6/25/2014	Chamber	96	78.91	36.91	16	20.329671
062514-D3	Wet	Slim	6/11/2014	6/25/2014	Chamber	96	80.16	39.16	16	20.818071
062514-D2	Wet	Slim	6/11/2014	6/25/2014	Chamber	96	77.85	38.05	16	20.818071
062514-F3	Wet	Deep	5/2/2014	6/25/2014	Lab / Mine	96	84.33	83.53	16	Unavailable
071014-A1	Hydrophobic	Slim	6/25/2014	7/10/2014	Chamber	96	64.4	39.5	16	20.573871
071014-A2	Hydrophobic	Slim	6/25/2014	7/10/2014	Chamber	96	65.4	40.5	16	21.794872
071014-A3	Hydrophobic	Slim	6/25/2014	7/10/2014	Chamber	96	64.85	37.75	16	20.329671
071014-B2	Hydrophobic	Slim	6/25/2014	7/10/2014	Chamber	96	62.95	40.25	16	20.818071
071014-B3	Hydrophobic	Slim	6/25/2014	7/10/2014	Chamber	96	61.54	38.54	16	17.277168
071014-C1	Hydrophobic	Slim	6/25/2014	7/10/2014	Chamber	96	61.16	38.86	16	15.811966
101714-E1/41B	DYWI	Deep		10/17/2014	Lab	82.43	82.43	59.59	20.75	21.794872
101714-E2/31B	DYWI	Deep		10/17/2014	Lab	64.14	64.14	43.3	16.01	20.329671
101714-E3/31B	DYWI	Deep		10/17/2014	Lab	62.28	62.28	41.42	16	20.818071
101714-G1/31B	DYWI	Deep		10/17/2014	Lab	60.55	60.55	38.73	15.14	20.329671
101714-G2/41B	DYWI	Deep		10/17/2014	Lab	77.33	77.33	57.82	19.34	21.794872
101714-G3/31B	DYWI	Deep		10/17/2014	Lab	61.8	61.8	45.56	15.48	19.96337
101714-I1/41B	DYWI	Deep		10/17/2014	Lab	76.97	76.97	49.61	19.24	20.818071
101714-I2/41B	DYWI	Deep		10/17/2014	Lab	63.88	63.88	39.12	16.01	19.96337
101714-21B-1	DYWI			10/17/2014	Lab	65.92	65.92	44.96	16.21	19.96337
101714-31B	DYWI			10/17/2014	Lab	48.91	48.91	28.47	16.26	21.794872
101714-21B-2	DYWI			10/17/2014	Lab	62.42	62.42	39.77	16	20.573871
101714-21B-3	DYWI			10/17/2014	Lab	63.74	63.74	37.25	16.01	19.96337
101714-B1		Slim		10/17/2014	Lab/Mine	64	64		16	22.283272
103114-K3	FoamDust	Deep	6/24/2014	10/31/2014	Lab	128	125.85	110.11	32	24.236874
103114-F2	FoamDust	Deep	6/24/2014	10/31/2014	Lab	128	123.84	107.78	32	21.794872
103114-F1	FoamDust	Deep	6/24/2014	10/31/2014	Lab	128	124.99	112.4	32	24.236874
103114-K2	FoamDust	Deep	6/24/2014	10/31/2014	Lab	128	125.06	110.67	32	21.794872
103114-H1	FoamDust	Slim	6/24/2014	10/31/2014	Lab	64	61.41	48.89	16	20.818071

103114-H2	FoamDust	Slim	6/24/2014	10/31/2014	Lab	64	60.4	46.64	16	20.818071
10314-H3	FoamDust	Slim	6/24/2014	10/31/2014	Lab	64	59.96	48.26	16	20.573871
030215-E3	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	136.06	118.26	32	26.06838
030215-E2	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	132.76	117.06	32	27.77778
030215-K3	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	125.71	111.91	32	21.55067
030215-G2	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	129.59	114.39	32	21.55067
030215-G1	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	128.17	103.37	32	22.28327
030215-F1	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	125.98	110.68	32	26.80098
030215-E1	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	130.57	111.07	32	16.54457
030215-I2	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	125.54	110.94	32	39.74359
030215-H1	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	129.36	113.26	32	23.26007
030215-G3	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	129.14	116.64	32	24.72528
030215-H3	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	137.08	122.58	32	21.79487
030215-F2	Hydrophobic	slim	11/11/2014	3/2/2015	Chamber	192	141.96	125.16	32	23.99267

BIBLIOGRAPHY

Adler, H.H., and Kerr, P. F., 1963, “Infrared absorption frequency trends for anhydrous normal carbonates,” *American Mineralogist*, Vol. 48, No.1-2, pp. 124.

Amyotte, P. R., Mintz, K. J., and Pegg, M. J., 1995, “Effect of rock dust particle size on suppression of coal dust explosions,” *Process safety and environmental protection,* Vol. 73, No. 2, pp. 89-100.

ASTM E1226 – 10. “Standard Test Method for Explosibility of Dust Clouds.”
Siwek, R. “Development of a 20 ltr laboratory apparatus and its application for the investigation of combustible dusts”, Ciba Geigy AG, Basel, Switzerland, 1985.

Cashdollar, K., Hertzberg, M. 1985, “20-L explosibility test chamber for dusts and gases,” *Review of Scientific Instruments*, Vol. 56, No. 596 doi: 10.1063/1.1138295

Cashdollar, K.L., Hertzberg, M. (1989). Laboratory Study of Rock Dust Inerting Requirements: Effects of Coal Dust Volatility, Particle Size, and Methane Addition. *Department of the Interior, U.S. Bureau of Mines, Technical Paper, 965-974*

Cashdollar, K.L., 1996, “Coal dust explosibility,” *Journal of Loss Prevention in the Process Industries*, Vol. *9*, No.1, pp. 65-76.

Cashdollar K.L., M.J. Sapko, E.S. Weiss, M.L. Harris, C. Man, S.P. Harteis, G.M. Green (2010). Recommendations for a New Rock Dusting Standard to Prevent Coal Dust Explosions in Intake Airways. NIOSH RI 9679.

Christakis, N., Wang, J., Patel, M.K., Bradley, M.S.A., Leaper, M.C., Cross, M. 2006, “Aggregation and Caking Processes of Granular Materials: Continuum Model and Numerical Simulation with Application to Sugar,” *Advanced Powder Technol*, Vol 17, No.5, pp. 543-565.

Cortese, R.A., M.J. Sapko (1991), Flame Powered Trigger Device for Activating Explosion
Suppression Barrier. USBM RI 9365.

Dastidar, A. G., Amyotte, P. R., and Pegg, M. J., 1997, “Factors influencing the suppression of coal dust explosions,” *Fuel*, Vol.76, No. 7, pp. 663-670.

Forbes, J.J. (1939). Methods of Rock-Dusting America Coal Mines. *Department of the Interior, U.S. Bureau of Mines, Report of Investigation, 3465, 4-7.*

Greenwald, H.P. (1938). Recent Trends in Rock Dusting to Prevent Dust Explosions in Coal Mines. *American Institute of Mining and Metallurgical Engineers, Technical Paper, 975. 1-13.*

Grumer, J. (1973). Recent Developments in Coal Mine Fire and Explosion Prevention Research. *Department of the Interior, U.S. Bureau of Mines, Information Circular, 8616, 2-7.*

Hartmann I., Nagy, J., Howarth, H.C., Sachs, A. (1950) Recent Rock-Dusting Experiments for Arresting Coal-Mine Explosions. *Department of the Interior, U.S. Bureau of Mines, Report of Investigation, 4688,* 3-15.

Hartmann, I., Westfield, J. 1956, "Rock Dusting and Sampling Including Wet Rock Dusting, at the Bureau of Mines Experimental Coal Mine," U.S. Bureau of Mines Information Circular IC 7755, 13pp.

Hertzberg, M., Cashdollar, K., Opferman, J. (1979) The Flammability of Coal Dust-Air Mixtures: Lean Limits, Flame Temperatures, Ignition Energies, and Particle Size Effects. *Department of the Interior, U.S. Bureau of Mines, Report of Investigation, 8360.*

Hertzberg, M., Cashdollar, K., Zlochwer, I. 1988, "Flammability Limit Measurements for Dusts and Gases," *21st Symposium (International) on Combustion,* The Combustion Institute. West Germany Aug. 3-8, 1986 p 303-313.

Huang, Q., Honaker, R., Perry, K., Lusk, B. 2015, "Surface Chemistry Modification of Rock Dust for Improved Dispersion and Coal Dust Explosion Prevention," SME Preprint 15-052. Littleton, CO: SME.

Lusk, B. (2013). Test Report for DSI Underground Systems Inc. Dry Rock Dust vs. DYWI Dust 38L Chamber Tests. Technical Paper.

Man, C. K., and Teacoach, K. A., 2009, "How does limestone rock dust prevent coal dust explosions in coal mines?" *Mining Engineering*, Vol. 61, No. 9, pp. 69.

McPherson, M. 2009. *Subsurface Ventilation Engineering.* California: Mine Ventilation Services.

Mine Safety and Health Administration – United States Department of Labor. 2015. Title 30 Code of Federal Regulations. http://www.msha.gov/30cfr/75.402.htm. Accessed January 2015.

Mine Safety and Health Administration – United States Department of Labor. 2015. Title 30 Code of Federal Regulations http://www.msha.gov/30cfr/70.100.htm. Accessed January 2015.

Mine Safety and Health Administration – United States Department of Labor. 2015. Title 30 Code of Federal Regulations http://www.ecfr.gov/cgi-bin/text-idx?SID=cc983cb2a875ad8fb93141ff72c527f9&mc=true&node=se30.1.75_12&rgn=div8 . Accessed May 2015.

Mine Safety and Health Administration – United States Department of Labor. http://www.msha.gov/MSHAINFO/FactSheets/MSHAFCT8.HTM. Accessed August 2015

Mine Safety and Health Administration – United States Department of Labor. Major provisions and Effective Dates MSHA's Final Rule to Lower Miners' Exposure to Respirable Coal Mine Dust. http://www.msha.gov/endblacklung/docs/summaryEffectiveDates.pdf accessed May 2015.

Mine Safety and Health Administration – United States Department of Labor. History of Mine Safety and Health Legislation. http://www.msha.gov/MSHAINFO/MSHAINF2.HTM. Accessed August 2015

Mine Health and Safety Administration. 2014 Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors: Final Rule. Federal Register Vol. 79, NO. 84. Washington, D.C. Department of Labor.

National Institute of Occupational Safety and Health – Center for Disease Control. 2006. http://www.cdc.gov/niosh/nas/mining/pdfs/theminingprogram.pdf. Accessed September 2015.

Pinkley, J., Masloff, B., Brown, B., Thorogood, S. 2012, DSI DYWI Rock Dust Enhancing Safety and Productivity in Underground Coal Mining. SME Preprint No.12-043. Littleton, CO: SME.

Rice, G.S., Frazer, J.C.W., Larsen, A., Haas, F., Scholz, C. (1911). The Explosibility of Coal Dust. *Department of the Interior, U.S. Bureau of Mines, Bulletin, 20.84-97, 107-108.*

Rice, G.S., Jones, L.M. (1915). Methods of Preventing and Limiting Explosions in Coal Mines. *Department of the Interior, U.S. Bureau of Mines, Technical Paper 84. 14-26.*

Rice, G.S., Jones, L.M., Egy, W. L., Greenwald H.P. (1922). Coal Dust Explosion Tests in the Experimental Mine 1913 to 1918, inclusive. *Department of the Interior, U.S. Bureau of Mines, Bulletin, 167. 21-29.*

Rice, G.S., Greenwald, H.P. (1929). Coal-Dust Explosibility Factors Indicated by Experimental Mine Investigations, 1911 to 1929. *Department of the Interior, U.S. Bureau of Mines, Technical Paper, 464. 5-12.*

Rice, G.S., Greenwald, H.P., Howarth, H.C. (1930). The Effectiveness of Different Size Rock Dusts in Preventing Coal-Dust Explosions in Mines. *Department of Commerce, U.S. Bureau of Mines, Report of Investigation, 3034.2-7.*

Richmond, J. K., Liebman, I., and Miller, L. F., 1975, "Effect of rock dust on explosibility of coal dust," US Dept. of the Interior, Bureau of Mines, 38 pp.

Sapko, M.J., A.L. Furno, J.M. Kuchta (1977). Quenching Methane Air Ignitions With Water Sprays, USBM RI 8214.

Sapko, M. J., Weiss, E. S., Cashdollar, K. L., & Zlochower, I. A. (2000). Experimental mineand laboratory dust explosion research at NIOSH. *Journal of Loss Prevention in the ProcessIndustries*, 13, 229–242.

USEPA – United States Department of the Interior. 2015. Toxics Release Inventory – Chemical Report.http://iaspub.epa.gov/triexplorer/release_chem?p_view=USCH&trilib=TRIQ1&sort=_VIEW_&sort_fmt=1&state=All+states&county=All+counties&chemical=All+chemicals&industry=ALL&year=2013&tab_rpt=1&fld=RELLBY&fld=TSFDSP. Accessed February 2015.

VITA

Robert Quentin Eades was born on in Lexington, Kentucky to Kenneth and Laura Eades. He attended the University of Kentucky in Lexington, Kentucky, and was awarded a Bachelor of Science Degree in Mining Engineering with Magna Cum Laude honors. Upon graduation, he continued his education at the University of Kentucky. He was awarded an assistantship and works as both a research and teaching assistant to Dr. Kyle Perry. He expects to graduate in May 2016 with a Master of Science in Mining Engineering. He has been a member of SME since 2009.