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MANAGEMENT OF COAL DUST EXPLOSIONS IN UNITED STATES' COAL MINES USING BAG TYPE PASSIVE EXPLOSION BARRIERS

by

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A THESIS

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Approved by

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ABSTRACT

The most significant and powerful hazard that exists in an underground coal mine is a coal dust explosion. A coal dust explosion has the potential to propagate throughout a mine resulting in massive damage to the mine and equipment, as well as tragic loss of life. An assessment of current global regulations and practices uncovered four main control methods utilized to prevent coal dust explosions in coal mines world-wide. The United States is one of the few countries that does not regulate or employ all four of these safety practices. Additionally, a review of past research into coal dust explosions and their prevention and mitigation uncovered scientific need for the use of explosion barriers as an additional line of defense against deadly coal dust explosions since the early 1900s. This research project was developed to investigate the possibility of implementing the fourth prevention strategy in the United States, the use of explosion activated barriers as the last line of defense against the propagation of a coal dust explosion.

The goal of this thesis was twofold. The first component was to demonstrate that explosion impulse, as opposed to explosion pressure, is the primary factor in the complete operation of the bag barrier system; meaning the rupturing of the bag, the release of the contained stone dust, and the dispersal of the released dust. The second component was to demonstrate that the bag barrier system can be effectively implemented into American underground coal mines. This goal was achieved through the careful examination and analysis of historical mine explosions and mine explosion prevention research, explosive testing of the bag barrier system, and trial bag barrier installations in operating coal mines.

DEDICATION

To my wife Jennifer, and son David, for their unwavering confidence, love, support, and encouragement. To my parents, Ann and Robert, for all the love, support, and blessings they have given me throughout my life.

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I would like to thank Dr. David Humphreys, and Mr. Terry O'Beirne from Skillpro Services of Queensland, Australia. Their expertise and years of experience, research, and development with the bag barrier product, along with the wealth of information, insights, and guidance that this afforded, were instrumental to the project.

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NOMENCLATURE

Symbol/Abbreviation	**Description**
# Mesh	A sieve having said number (#) of wires per inch, a higher # mesh has finer wire and smaller opening sizes
Afterdamp	Toxic gases developed during methane and coal dust explosions and remain afterwards
BEM	Bruceton Experimental Mine
Bleeder or Bleeder Entry	Mine entries utilized for allowing ventilation into the gob/goaf behind the longwall panel to reduce methane accumulations
USBM	United States Bureau of Mines
C4	A high yield chemical explosive compound comprised of RDX, a binder, a plasticizer, and a marker or taggant chemical
CFR	Code of Federal Regulations
Coal Dust	Fine coal particles produced during the mining and transportation processes
CSIR	Council of Scientific and Industrial Research
Davy, Clanny, or Stephenson Lamps	Types of flame safety lamps used by miners for light in the mines that reduced the open flame's ability to ignite methane gas
Face	Part of mine where actual mining occurs via longwall shear or continuous miner, where the machine liberates the ore
Firedamp	Methane Gas
Flue Dust	Ash from the flue or chimney of a coal or wood furnace
G or g	Grams
Gate-road	Mine development road at either end of the longwall panel

Gob or Goaf	Region behind the advancement of the longwall panel that is allowed to collapse or subside from lack of support
Headgate	The gate-road at the beginning of the longwall shear's path, nearest to the intake developments
Inby or Inbye	The direction that goes deeper into the mine from a given location
Intake Airway	Mine entry used for incoming fresh air distribution
Kg or kg	Kilograms
KPA or kPa	Kilo Pascals
MESA	Mine Enforcement Administration
Mine Working	Mine entry or tunnel
psi*ms	A unit of impulse, the integral of a pressure versus time curve, pounds per square inch milliseconds
MSHA	Mine Safety and Health Administration
Neutral Airway	Mine entry used for conveyor belt routing, usually between the intake and return entries
NIOSH	National Institute for Occupational Safety and Health
NSW	New South Wales
NZ	New Zealand
Outby or Outbye	The direction that goes toward the mine opening from a given location
Panel	Large section of mine surrounded by developments and left to be mined via a longwall method
Penitent or Cannoneer	Miner charged with locating and igniting methane pockets in the mine to burn off small gas accumulations
Portal	A mine opening large enough for men and equipment to pass through

PSI or psi	Pounds per square inch
Quick Flaming Explosives	Permissible Explosives (Low/No flame producing)
RDX	An organic explosive compound used primarily by military. Also known as cyclonite, hexogen, or trimethylenetrinitramine
Return Airway	Mine entry used to return the contaminated air to outside the mine
Rock Dust or Stone Dust	Pulverized limestone or shale rocks
Rock Dusting or Stone Dusting	The practice of the widespread distribution or 'dusting' of the coal mine floor, walls, and ceiling with pulverized rock dusts
RSA	Republic of South Africa
Sackcloth	Cloth sacks of a relatively fine weave so to contain the various food staples that were supplied and delivered in them
Seals or Stoppings	Walls built in place in a mine after development and hitched into the floor, walls, and roof. Can be temporary or permanent
Shooting	Using explosives to liberate ore in a mine
Tailgate	The gate-road at the end of the longwall shear's path, nearest to the return developments
TIC	Total Incombustible Content - a measure of the % of incombustible content of a sample of accumulated dust from a coal mine
U.S.	United States of America
UBB	Upper Big Branch
UK	United Kingdom
USGS	United States Geological Survey
WVMHS	West Virginia Miner's Health and Safety Administration

1. INTRODUCTION

1.1. PROBLEM STATEMENT

The most significant and powerful hazard that exists in an underground coal mine is a coal dust explosion. A coal dust explosion has the potential to propagate to every part of a mine and result in massive damage to the mine and equipment, as well as tragic loss of life. Since 2001, disasters due to coal dust explosions in U.S. underground coal mines have caused 59 deaths, including 29 deaths in a single mine explosion at the West Virginia Upper Big Branch (UBB) mine in 2010. Many controls have been developed and implemented in different countries to reduce the impact of coal dust explosions.

One of the most significant health and safety interventions in use internationally is the “Bag Barrier” passive explosion barrier. Both active and passive barrier systems have been developed and are on the market, but the bag barrier system is the most common due to ease of installation and lower costs. Though various explosion barrier types have been in use in other countries for over 15 years, their use has not been adopted in the United States. This is due to the false belief that good housekeeping and other preventative strategies (such as the practice of “rock dusting”) will always be 100% effective. Following the UBB disaster, many have realized that additional defenses are needed to prevent the propagation of a methane ignition into a coal dust explosion. From a risk management viewpoint, the explosion barriers are a supplemental and final contingency control for the rare occasion when one or more of the employed prevention strategies is insufficient or fails to stop the propagation of the explosion. Research and revised guidelines specific to U.S. mines are needed to demonstrate the practical application of bag barriers as supplemental protection, in addition to currently regulated safeguards, to prevent explosion propagations. The research presented in this thesis investigates the operation of the bagged stone dust barrier system, the possibilities of implementing the bagged stone dust style of explosion barrier into U.S. underground coal mines, and any modifications or design changes required for their implementation.

1.2. RESEARCH APPROACH

The approach taken with this project is qualitative through visual analysis of the bag barrier performance as well as survey analysis of mine workers in proximity to the bag barrier system to define design changes that would encourage the bag barrier system use in the United States. Additionally, quantitative research was performed through open air and shock tunnel explosives testing and data analysis, and a year-long moisture intrusion study. Extensive research has been completed on the use of the bag barrier type of explosion barrier by the manufacturer and the performance of this barrier system has been comprehensively tested and demonstrated by numerous mines in Australia, New Zealand, South Africa, Poland, and the United Kingdom. The primary challenges to the implementation of this technology in the United States is to change the current mining culture and refine existing regulations, or develop new guidelines, for the design and installation of bag barriers in U.S. coal mines. Additional challenges include mines where the mining height may be low or the bleeder returns off the longwall face present unique explosion suppression issues.

This project was primarily developed to address the technical aspects of the implementation of the bag barrier system into underground coal mines in America, and to define any necessary modifications for their use. This goal was divided into 3 main objectives (Table 1.1). Each of these main objectives were comprised of a various number of tasks required to attain their respective goal. A brief synopsis of the over-arching purpose of, and approach to, each objective is given in this section. A detailed description and explanation of each objective and its sub-tasks are contained in their respective sections (Sections 3, 4, and 5) within this Thesis.

Table 1.1: Project Objectives

[redacted]

1.2.1. Operation of Bag Type Passive Explosion Barriers. The purpose of this objective was to understand the principle operational characteristics of the bag type passive explosion barriers. The tasks required to complete this objective involved specifically designed experiments to test the bags' response to various levels of pressure and pressure over time, defined as impulse. The testing performed during this project utilized high explosive charges to produce the various levels of pressure and impulse that the barrier bags were subjected to. This was done to obtain the pressure and impulse levels required for bag rupture, but without the heat, turbulence, and movement of large volumes of air and hot gasses that would be observed with a methane gas explosion. The purpose for this distinction is so that the bag rupture characteristics could be studied separately from the distribution of the contained stone dust. This differentiation was imperative to understanding the value that each component of a coal dust explosion (pressure, impulse, and air movement) have on the operation of the bagged stone dust type passive explosion barrier system.

1.2.2. Implementation of Bag Type Passive Explosion Barriers in U.S. Coal Mines. The purpose of this objective was to understand the inherent physical difficulties and obstructions to the installation and possible implementation of the bag type passive explosion barrier systems into U.S. coal mines. Two mines of differing heights and configurations, representing a wide cross-section of U.S. coal mines were selected to perform scaled-length trial bag barrier installations. The barriers were installed in entries ahead of major development, and left in place for a period of time so the miners would experience working around them during the normal progression of mining activities. After a period of time, mine site staff were surveyed on their experiences working around the barriers, insights into any problems experienced or foreseen, and concerns that may have arisen from their interactions with, or observations of, the barriers. This objective provided first-hand knowledge and experience with the installation of a bag barrier in American coal mines, which was necessary to prove that it was not only possible, but quite feasible.

1.2.3. Required Changes or Improvements for Use of Bag Type Explosion Barriers in U.S. Coal Mines. The purpose of this objective was to assess the need for any changes or improvements, required by either the mines or the barriers, for the implementation and use of such barriers on a full scale and long-term basis in underground coal mines in the United States. This objective was needed to explore whether the regulations currently used in other countries were comprehensive enough to account for differences between foreign and American coal mines. This objective was approached on three fronts. First, through a complete review of regulations pertaining to coal mining and explosion prevention strategies utilized in countries that employ explosion barriers and those of the United States. Second, by involving two consultants, Dr. David Humphreys and Mr. Terry O’Beirne of Skillpro Services Pty. Ltd. They have a great deal of experience and knowledge in the research, development, and implementation of bag barriers in other countries. The third front was incorporating feedback obtained through various means from a variety of coal industry laborers, professionals, executives, regulators, and researchers. The information gleaned from the many discussions, meetings, and presentations with countless people, in addition to that gained from the Australian consultants, was utilized to assess and outline the changes needed to implement the use of bag type passive explosion barriers in U.S. coal mines.

2. BACKGROUND

2.1. BACKGROUND OVERVIEW

The background research required for the completion of this project was diverse. To be comprehensive, it started with the history of coal mining and coal mine explosions in the United States (Section 2.2.). This was followed by reviewing the history of coal mine explosion prevention research and strategies (Section 2.3.). This historical examination, and the contained knowledge became the foundation upon which the remainder of the project was based. This review continued with a look at current practices utilized in coal mines within the United States and abroad (Section 2.4.). The assessment of the current practices uncovered four main coal dust explosion prevention strategies in use around the globe. However, the United States only uses three of these four strategies. The fourth strategy that is not utilized in the United States is the use of explosion barriers; even though all earlier research performed in the United States and abroad indicates the need for this extra level of protection.

During the review of foreign coal mining regulations and practices, the requirement for the use of explosion barriers was predominant. The type of explosion barrier to be used was not dictated, but many regulations had included sections, or separate documents, outlining the use of a bagged stone dust type of explosion barrier. The history, development, and testing of these bag barriers was researched and evaluated (Section 2.5.). Finally, the barrier bags themselves would be tested further to understand and outline their operational characteristics. This testing was to be performed using high explosive charges in open and confined testing arrangements, so the applicable aspects of explosive testing and shock and pressure propagation were studied (Section 2.6.).

2.2. HISTORY OF COAL MINING AND RELATED EXPLOSIONS IN THE UNITED STATES

As long as there have been underground coal mines, there have been explosions fueled by the gas and dust released within them. These explosions have caused the injury and death of many miners and the destruction of mine workings in all countries where the fuel source is mined. The first reported coal mine explosion in the United States occurred in Virginia in 1810[1]. Though mining, ventilation, and prevention equipment and practices have improved greatly over the past 200 years, coal mine explosions have unfortunately continued in the United States up until the latest example in 2010 in West Virginia[2].

Coal mining in the United States dates back to early settlers. Initially wood was plentiful and easily obtained, with only limited quantities of coal being converted to charcoal for special purposes. In 1702, coal obtained from the outcrops along the James River in Virginia was mined for use in blacksmith forges[2]. The digging of coal for local use at this location continued for fifty plus years before the product began to be heavily mined and shipped via the river. In 1760, another mine was developed near Richmond, Virginia called Heath's Pits.

By 1810 at least three of the shafts being worked at Heath's Pits were 300 feet deep. At this depth problems with current ventilation techniques began to occur and pockets of methane gas (then called firedamp) would form explosive mixtures in poorly ventilated mine workings[2]. Additionally, the miners of the time would use open flame lamps mounted to their helmets for light to work by while employing black powder and dynamite to break the rock and coal. With the combination of an open flame lamp at the highest point on a miner's body, the use of large fireball producing explosives, and the collection of explosive mixtures of methane that are lighter than air and collect at the high points in the mine workings, gas explosions were imminent.

Even with the use of the newly developed Flame Safety Lamp in 1815, explosions continued to occur. Many explosions still occurred from open flames due to the miners removing the wire mesh covers from their safety lamps. They did this because it limited the light output of the lamp[2]. Additionally, many mines were reserved to using older methods of locating methane pockets using open flames, and igniting the accumulations intentionally.

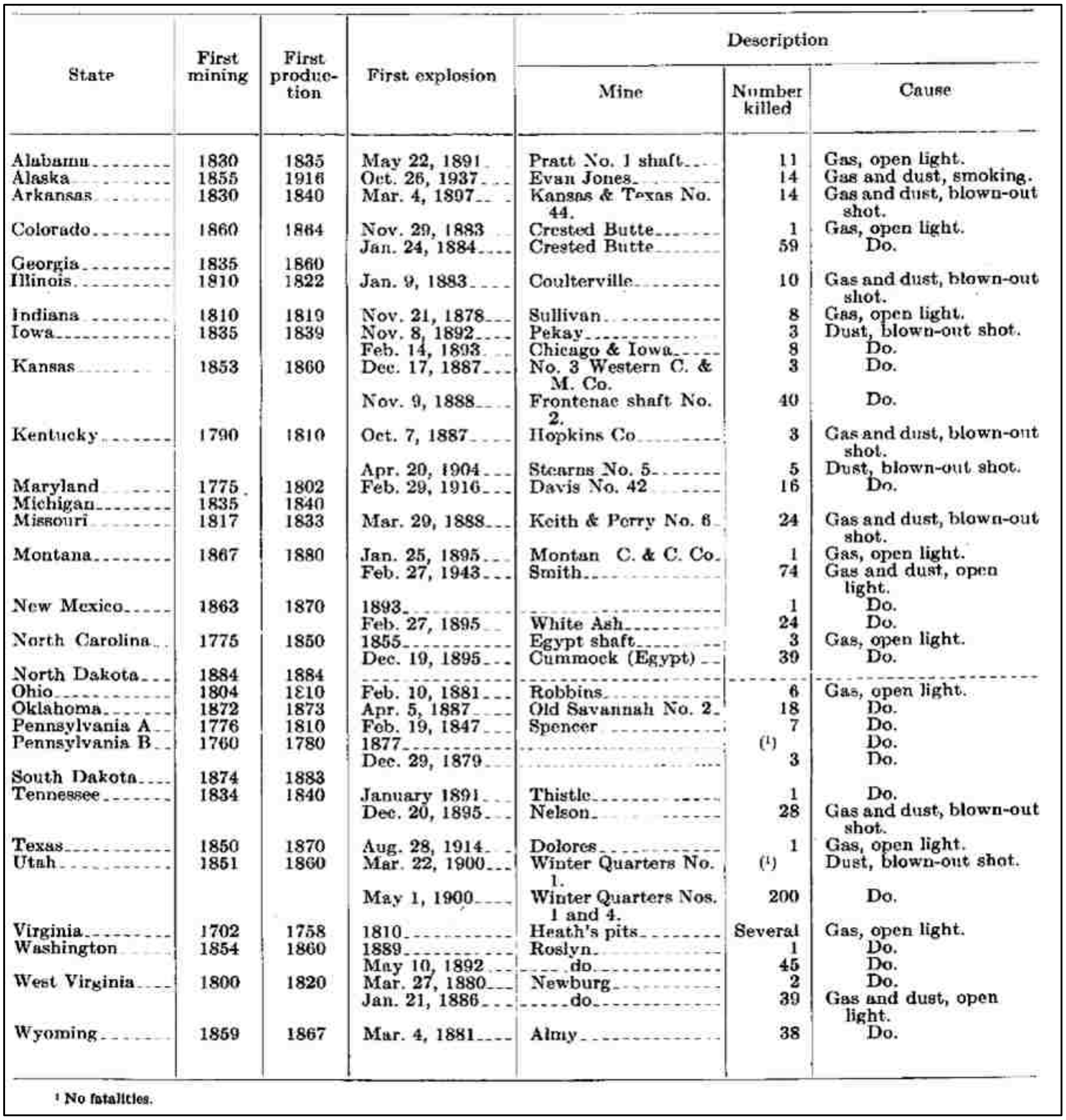
As the population of the United States began to sprawl along with the transportation system, so did the number of coal mines in the various coal-producing regions in the United States; such as the Powder River Basin, Illinois Basin, and Appalachian regions. As these mines progressed toward larger production capabilities, the number of coal mine explosions in those regions also increased. This is supported by examining the time interval between when mining began and when production began compared to the date of the first explosion. In states where mine production began before 1820, an average of 75 years passed before their first coal mine explosion. In states where mining production began between 1820 and 1850, an average of 60 years passed before their first coal mine explosion. In states that began mine production after 1850, the average time before a mine explosion had decreased to 20 years[2]. The shrinking time interval between the beginning of production and the first explosion indicates the increased rate at which coal mines were being developed to a stage favorable to such explosion conditions as compared to the earlier mines, which were developed mostly by hand.

Moreover, this theory is solidified by looking at the production values over the same time period. For example, when coal production began in Colorado in 1864, the annual production was a mere 500 tons per year. By 1869 it had increased to 10,000 tons per year, and by 1875 it had reached 100,000 tons per year. When the first deadly explosion occurred in 1883, the production output was over 1.25 million tons[2]. Table 2.1 displays the dates of first coal mining activities, first production mining activities, and the first deadly explosions by state.

In addition to the increased occurrence of coal mine explosions was an increase in the number of miners killed. From 1839 to 1890, 43 coal mine explosions occurred, killing 851 miners[3]. In the following 10 years (1891 through 1900), the occurrence of coal mine explosions continued to increase with 38 coal mine explosions killing 1,024 miners, and between the years of 1901 and 1910 their occurrence over tripled, with 111 coal mines experiencing explosions that killed 3,321 miners[3]. The public outcry over the sharp increase in coal mine explosions and the loss of life incurred, forced the U.S. Congress to act.

Until this point, in the United States it was believed that the ignition of methane gas, or firedamp, was the primary cause of coal mine explosions. However, the part that the coal dusts (created by the mining practices used in liberating the coal from the ground) was playing in the frequency, magnitude, and devastating results of coal mine explosions, was being questioned due to research recently performed in Europe along with recent coal mine explosions occurring in dry, dusty, non-gassy mines[2]. This theory regarding the involvement of coal dusts in coal mine explosions had been a hot topic in Europe for some time[5].

Table 2.1: First Coal Mining and First Explosions by States[2]



State	First mining	First production	First explosion	Description		
				Mine	Number killed	Cause
Alabama	1830	1835	May 22, 1891	Pratt No. 1 shaft	11	Gas, open light.
Alaska	1855	1916	Oct. 26, 1937	Evan Jones	14	Gas and dust, smoking.
Arkansas	1830	1840	Mar. 4, 1897	Kansas & Texas No. 44.	14	Gas and dust, blown-out shot.
Colorado	1860	1864	Nov. 29, 1883	Crested Butte	1	Gas, open light.
			Jan. 24, 1884	Crested Butte	59	Do.
Georgia	1835	1860				
Illinois	1810	1822	Jan. 9, 1883	Coulterville	10	Gas and dust, blown-out shot.
Indiana	1810	1819	Nov. 21, 1878	Sullivan	8	Gas, open light.
Iowa	1835	1839	Nov. 8, 1892	Pekay	3	Dust, blown-out shot.
			Feb. 14, 1893	Chicago & Iowa	8	Do.
Kansas	1853	1860	Dec. 17, 1887	No. 3 Western C. & M. Co.	3	Do.
			Nov. 9, 1888	Frontenac shaft No. 2.	40	Do.
Kentucky	1790	1810	Oct. 7, 1887	Hopkins Co	3	Gas and dust, blown-out shot.
			Apr. 20, 1904	Stearns No. 5	5	Dust, blown-out shot.
Maryland	1775	1802	Feb. 29, 1916	Davis No. 42	16	Do.
Michigan	1835	1840				
Missouri	1817	1833	Mar. 29, 1888	Keith & Perry No. 6	24	Gas and dust, blown-out shot.
Montana	1867	1880	Jan. 25, 1895	Montan C. & C. Co.	1	Gas, open light.
			Feb. 27, 1943	Smith	74	Gas and dust, open light.
New Mexico	1863	1870	1893		1	Do.
			Feb. 27, 1895	White Ash	24	Do.
North Carolina	1775	1850	1855	Egypt shaft	3	Gas, open light.
			Dec. 19, 1895	Cummock (Egypt)	39	Do.
North Dakota	1884	1884				
Ohio	1804	1810	Feb. 10, 1881	Robbins	6	Gas, open light.
Oklahoma	1872	1873	Apr. 5, 1887	Old Savannah No. 2	18	Do.
Pennsylvania A	1776	1810	Feb. 19, 1847	Spencer	7	Do.
Pennsylvania B	1760	1780	1877		[1]	Do.
			Dec. 29, 1879		3	Do.
South Dakota	1874	1883				
Tennessee	1834	1840	January 1891	Thistle	1	Do.
			Dec. 20, 1895	Nelson	28	Gas and dust, blown-out shot.
Texas	1850	1870	Aug. 28, 1914	Dolores	1	Gas, open light.
Utah	1851	1860	Mar. 22, 1900	Winter Quarters No. 1.	[1]	Dust, blown-out shot.
			May 1, 1900	Winter Quarters Nos. 1 and 4.	200	Do.
Virginia	1702	1758	1810	Heath's pits	Several	Gas, open light.
Washington	1854	1860	1889	Roslyn	1	Do.
			May 10, 1892	do	45	Do.
West Virginia	1800	1820	Mar. 27, 1880	Newburg	2	Do.
			Jan. 21, 1886	do	39	Gas and dust, open light.
Wyoming	1859	1867	Mar. 4, 1881	Almy	38	Do.

[1] No fatalities.

During the five-year period from the inception of the Bureau of Mines in late 1910 through 1915, another 45 coal mine explosions occurred killing another 1,546 miners. From 1916 through 1920, the number of explosions declined to 37, while the death toll from those explosions declined to 601. The trend of large death tolls due to coal mine explosions continued between 1921 and 1925 with 50 explosions resulting in the death of 1,329 miners. These numbers spiked between 1925 and 1930 with 54 explosions resulting in 1,794 deaths. With recent United States Bureau of Mines (USBM) research released in 1927 recommending the use of the Taffanel rock dust explosion barriers or the American ”Rice” versions located strategically in the mines, in addition to the recommended general dusting of the mine, the explosion occurrence and death toll greatly declined in the 1930s. The period of 1930 through 1935 saw only 16 explosions resulting in 247 deaths. While the period from 1936 through 1940 saw 21 explosions and 521 deaths. The decreased numbers in the early 1930s occurred as many mines were shut down temporarily or closed permanently during the Great Depression[2].

The period between 1941 and 1950 saw a continual decrease in the number of explosions and death tolls. From 1941 through 1945, there were 26 explosions and 440 deaths, while from 1946 through 1950, there were 11 explosions and 238 deaths. During the period of 1951 through 1955, there were only 8 explosions that killed 184 miners. The death toll continued to decrease over the next five years (1956 -1960) with 9 explosions and 121 deaths[3]. Things remained largely unchanged for the next decade, with 8 explosions and 122 deaths from 1961 through 1965, and 4 explosions and 132 deaths between 1966 and 1970[3].

The following decade, from 1971 through 1980, saw a drastic decline with only 4 explosion disasters and 36 related deaths[3]. Additional regulatory changes also occurred during this time frame. In the decades since the inception of the Mine Act (1977), the occurrence of coal mine explosions has greatly decreased. Between 1981 and 1990, 6 explosions caused the death of 60 miners. Between 1991 and 2000, only 1 coal mine explosion occurred resulting in the death of 8 miners. The early 2000s saw a resurgence of coal mine explosions with 4 disasters killing 59 miners[3]. This spike in explosions and deaths is possibly attributed to the complacency of a newer generation of miners, mine managers, and mine inspectors that had not been in the industry during the previous decades of frequent explosion disasters, and were therefore not sufficiently aware of the dangers of coal dust explosions. It is also possible that hard economic times for the coal industry had forced some mine managers to cut corners, resulting in the unsafe conditions that lead to explosions disasters. It is quite likely a product of both.

Though the frequency of coal mine explosion disasters has subsided and the resulting death tolls have dramatically decreased, the risk of coal dust explosions has not disappeared. Additionally, though their frequency and human costs have decreased over time, the economic costs of a coal mine explosion and loss of production can still cause the demise of even the strongest coal mining company. Such was the case with the holding company for the Upper Big Branch mine, Massey Coal, due to the most recent explosion in U.S. history in 2010. This further highlights the economic risks of coal dust explosions, in excess of the risks to human life. This also shows that even in these modern times, coal dust explosion tragedies continue to occur, albeit less frequently despite the regulations and practices currently in use.

2.3. HISTORY OF FOREIGN COAL MINE EXPLOSION DISASTERS

Coal mine explosions are not unique to the American coal mining industry. They have been experienced in all coal mining countries over the years. However, regulatory changes have occurred at different times in different countries. For example, stone dusting became standard practice in the UK in 1920, but Australia did not impose such standards until 1941[48]. Table 2.2 lists coal mine explosion disasters for Australia.

Table 2.2: Australian Coal Mine Explosion Disasters[48]

[redacted]

The Republic of South Africa has only two reported incidents of coal mine explosions in recent history with 68 miners killed in 1983, and 53 miners killed in 1993. Coal mine explosions affect large and small mining countries alike. The small country of New Zealand is not immune to such tragedies as indicated in Table 2.3. Even larger countries with longer coal mining histories, like Great Britain and Ireland, are susceptible to coal mine explosion tragedies, as indicated in Table 2.4. Aside from one coal mine explosion in New Zealand in 2010, reportedly due to inadequate and careless safety practices, there has not been a coal mine explosion in the foreign countries discussed in over 20 years, including the time since explosion barriers have been implemented in these countries.

Table 2.3: New Zealand Coal Mine Explosion Disasters[49]

New Zealand Mine Disasters		
Location	**Year**	**Fatalities**
Kaitangata	1879	34
Brunner	1896	65
Ralph’s Mine, Huntley	1914	43
Dobson Mine	1926	9
Glen Afton Mine	1939	11
Strongman Mine	1967	19
Pike River	2010	29
	TOTAL	**210**

Table 2.4: British and Irish Coal Mine Explosion Disasters[50]

British and Irish Mine Disasters		
Location	**Year**	**Fatalities**
Felling Mine	1812	92
Haswell Colliery	1844	95
Lletty Shenklin Mine	1849	52
Rhondda Colliery	1856	114
Lundhill Colliery	1857	189
Risca Blackvein	1860	146
Oaks Colliery	1866	361
Ferndale Colliery	1867	178
Ferndale Colliery	1869	53
Swaithe Main Colliery	1875	143
Blantyre Colliery	1877	207
Abercarn Colliery	1878	268
Wood Pit Colliery	1878	189
Dinas Rhondda	1879	62
Seaham Colliery	1880	164
New Risca Pit	1880	120
Naval Steam Colliery	1880	101
Clifton Hall Colliery	1885	178
Mardy Colliery	1885	81
Llannerch Colliery	1890	176
Parc Slip Colliery	1892	110
Combs Pit	1893	139
Great Western Mine	1893	63
Albion Colliery	1894	290
Peckfield Colliery	1896	63
Tylorstown	1896	57
East Side Pit	1901	83
National Colliery	1905	119
Maypole Colliery	1908	75
Burns Pit	1909	168
Wellington Colliery	1910	136
Cadeby Coal Mine	1912	88
Minnie Pit	1918	155
Bentley Coal Mine	1931	45
Wharncliffe Woodmoor Colliery	1936	58
Markham Colliery	1938	79
Sneyd Colliery	1942	57
William Pit	1947	104
Easington Colliery	1951	81
Six Bells Colliery	1960	45
Hampton Valley Colliery	1962	16
Tower Colliery	1962	9
Houghton Main	1975	5
Golborne Colliery	1979	10
	TOTAL	**5024**

2.4. HISTORY OF U.S. COAL MINE EXPLOSION PREVENTION RESEARCH AND STRATEGIES

In the 300 years since coal mining began in the United States, there have been a lot of explosions, and as a result, fatalities as well. The industry went from a period of very few explosions in its infancy, to a period of over 900 deaths per year due to explosions during its high point, and now has gone back to a period of less than 60 deaths due to explosions per decade as seen in Figure 2.1. Though this is a great reduction, any loss of life is too much. Therefore, the goal for coal mining explosion fatalities in the U.S. is zero. The final period of decreasing coal mine explosions and deaths can be attributed to an increased understanding of the phenomena through research, and the implementation and enforcement of scientifically based safety standards and protocols.

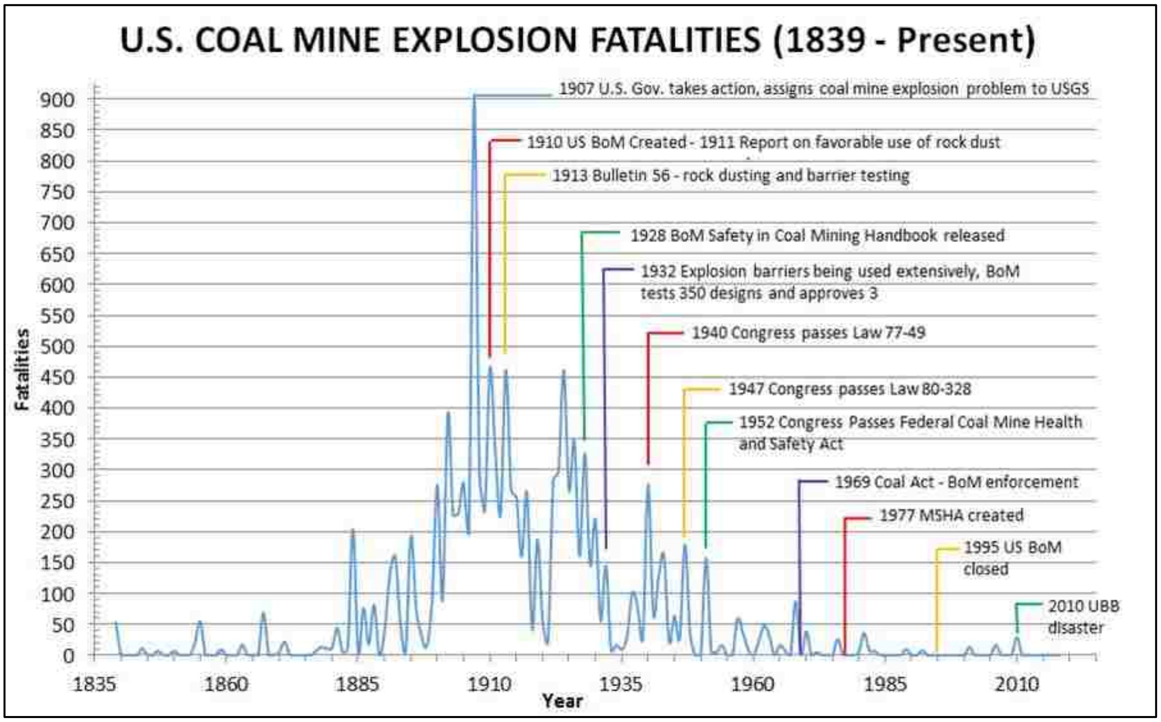


Figure 2.1: U.S. Coal Mine Explosion Fatalities and Major Prevention Milestones

Additionally, these changes were implemented during a time of increased coal production due to the world’s dependence on coal as an energy source. This fact highlights the significance of the changes made, and their effectiveness. So effective at reducing fatalities due to coal mine explosions that the Bureau of Mines was closed in 1995. However, since that time the fatality rate due to coal mine explosions is trending back up. This indicates that something has changed and additional safeguards are needed.

The earliest form of coal mine explosion prevention strategies was the penitent, or mine cannoneer. This was a miner who donned a wet sackcloth and crawled into areas of the mine suspected to contain accumulations of fire damp with an open flame lamp or candle held high. The miner would advance until the flame began to react with the firedamp by changing color and emitting small sparks. If the accumulation was not very large, the miner would extend his lit candle to ignite the pocket of gas over his body while covering his face and body with the wet cloth. If the accumulation was larger, the miner would extinguish his candle and retreat to a safe distance and use a device termed the “firing line” to pass a light attached to a cord over a wheel at the far end of the tunnel[2]. The person entrusted to perform this task, called “trying the candle”, was generally one of the more experienced and coolheaded of the miners. The French miners called this person ‘The Penitent’ due to the wet cloth resembling the hood of a monk; while most referred to this person as the mine’s cannoneer. This procedure and proper mine design for natural ventilation were the earliest of explosion prevention strategies[2].

As mines got deeper through the 1800s, ventilation became the primary focus of explosion prevention strategies. The methods utilized to increase airflow through the mine ran the gamut. In one example, large furnaces were built at the bottom of a shaft at one end of the mine to create an updraft in the shaft that pulled air through the mine[2]. A more modern approach was a bellows, or fan assembly, belt-driven by a steam engine. In 1891, the federal government responded to the increasing number of explosions due to insufficient ventilation by passing modest legislation that established minimum ventilation requirements in coal mines, and also prohibited mines from hiring children under the age of 12[4].

Another explosion prevention strategy of the time was ignition prevention. The early focus for this was the miners' lamps. Most were using hanging lamps or candles with open flames that could ignite flammable gasses[7]. Flame safety lamps, or Davy lamps, were invented around 1815 in Europe. The Clanny and Stephenson design safety lamps soon followed. The safety lamps gradually made their way to the U.S. along with immigrant miners[2]. The remainder of the century saw numerous iterations of the safety lamp design by a variety of companies. All incorporated wire mesh to cool the flame, but later models had made some improvements. These improvements came in the form of glass enclosures around the flame to increase light output, metal bonnets to protect the flame from being extinguished by gusts or drafts in the mine, or even gauges to measure the methane content of the air by the length of the blue tip of the flame[8]. Though safety lamps addressed the gas ignition concerns of an open flame lamp, it was not very popular among the miners. Many objected to their use because they were cumbersome and gave poor light, which reduced their efficiency. Since most miners were paid by the pound of ore that they mined, a reduction in efficiency was the same as a reduction in pay. Therefore, the risk of an explosion was a chance that many miners were willing to take. Additionally, many miners claimed that safety lamps gave a false sense of security, and were a substitute for the development of better ventilation systems, which most felt were desperately needed[9].

Nearing the turn of the 20th century, the common belief that all coal mine explosions were caused by the ignition of gasses was beginning to change. This change in thought was due to many contributing factors. First were the credible accounts of disaster witnesses and investigators. Additionally, numerous explosions had recently occurred in a grahamite mine in West Virginia, a flour mill in Minneapolis, and several dry, dusty coal mines in the bituminous fields and interior coal fields that were remarkably free of methane[5]. Furthermore, research was being done in Europe through the end of the 19th century as to the explosibility of coal dusts. In 1893 George S. Rice, a pioneer in the investigations and prevention of mine explosions in the United States, published his conclusions recognizing the mechanism of dust explosions[2].

Though miners were becoming more aware of the dangers of coal dust involvement in methane ignitions propagating into explosions, the numbers of explosions and deaths continued to increase. This was due, in part, to a change in the pay structure of the miners. Previously paid based on the amount of lump or screened coal produced, they were now being paid (after 1897) based on the run-of-mine coal produced[5]. This removed the incentive for the miners to cut the coal and use smaller black powder charges when shooting; and incentivized shooting down the most coal in the easiest manner. This led to the use of larger quantities of black powder and many overcharged holes per shot. Overcharging the holes led to more blown out or failed holes, which in turn led to burning powder being ejected into the mine tunnel where the recent pressure pulse from the detonation had scoured coal dust into a fine cloud. These conditions were ideal for igniting the coal dust and propagating an explosion further into the mine, and therefore the death toll continued to rise into the early 1900s. To counter this mining trend of shooting off the solid, and to curb the overcharging of black powder, many states passed laws limiting the maximum charge sizes allowed to be used and required that the shot firing be performed by qualified shot firers who inspected the holes prior to loading them[5]. In addition, since the coal dust explosion damage seemed worse in the intake airway, many mines slowed or stopped their fans during shot-firing to reduce the amount of fresh air and air pressure[5].

In June of 1907, the Secretary of the Interior transferred authority of the coal mine inspectors in the New Mexico and Indian Territory (including Oklahoma) to the U.S. Geological Survey (USGS) with the intent of lessening the number of coal mine explosions. The results of the inquiry were published in December the same year as Bulletin 333[10]. That year also proved to be one of the worst on record with over 1,400 miners killed by gas and dust explosions in coal mines. In response, Congress made an appropriation for the investigation of mine explosions, which became available July 1, 1908. The USGS was tasked with the investigation, and a testing facility was quickly established near Pittsburgh, Pennsylvania. The facility was opened for operation on December 3, 1908, and soon after began testing quick flaming explosives[5].

The years 1908, 1909, and the beginning of 1910 continued to see a preponderance of coal mine explosions, and in May of 1910, the U.S. Bureau of Mines was created within the Department of the Interior. Initially, their role was limited to research and investigation, having no inspection or enforcement authority until much later[4]. Investigations into coal dust explosions began immediately. In 1911, the newly formed Bureau of Mines had released Bulletin 20. This document is a comprehensive review of then-current research and disaster investigation reports, and the definition, origin, and distribution of coal dusts. Additionally, experiments were performed regarding the quality, density, coarseness, and chemical compositions of coal dusts using the test gallery developed by the USGS[5]. This early research showed favorable possibilities for the use of incombustible rock dust to prevent ignition of the coal dust, or at least limit the extent and violence of the incurred explosion.

The general and continued reluctance of the coal mining industry to accept the explosion hazards of coal dust spurred the director of the Bureau of Mines to develop a real, full-scale mine to continue their coal dust explosion experiments in. This would ensure that the validity of the results of the testing could not be argued, and would be "…accepted as conclusive"[11]. In 1913, the Bureau of Mines released Bulletin 56 reporting the results of the initial testing performed at the newly commissioned Bruceton Experimental Mine (BEM). Included in this round of testing were the effect of the French designed Taffanel Barrier, consisting of shelves of incombustible rock dust in the mine entry, on the ignition and severity of coal dust explosions. Researchers had commented on several of the tests that the flame of the explosion did not extend beyond the Taffanel Barriers[6]. These two early documents from the U.S. Bureau of Mines indicate the importance of rock dust in preventing or limiting the effects of coal dust explosions. Based on the information obtained from these early tests and the results of experiments performed around the world, the author and primary investigator of both reports, George Rice, began recommending the use of rock dust in coal mines[11].

Investigations and research continued in the area of limiting or preventing coal dust explosions with the use of rock dust, and in 1924 the USBM released Bulletin 225 titled Stone Dusting or Rock Dusting to Prevent Coal-Dust Explosions, as Practiced in Great Britain and France. The report reviews current research and practices in use throughout Europe. It reports that in 1920 Great Britain made stone dusting compulsory in coal mines that were dry and dusty, regulations which were later made more stringent. The author reports that the use of stone dusting is "…practically universal in British collieries"[12]. Though the efficiency of the method of application varies by mine, British regulations required that upon regular inspection of the roof, sides, and floor, the coal/rock dust mixture be maintained so that there not be more than 50% combustible materials[12].

Additionally, the Mines Department of France had approved the "schistification" (translated to shale dusting) of mines to prevent coal dust explosions[12]. Furthermore, the Taffanel Barriers were used as a secondary defense in many French mines. Similarly, the Germans were utilizing barrages of shelves supporting flue dust, rather than rock dust, and were also distributing the flue dust in the vicinity of shots being fired as well as along roadways. Along the roadways, the Germans were distributing flue dust by hand at a rate of 4.5 pounds of dust per lineal yard of roadway every 8 to 10 days[12]. This report is the first to mention an ideal ratio of coal to rock dust or the distribution of any prescribed amounts of incombustible matter.

During the same time frame in the United States, despite being recommended by the Bureau of Mines, only a handful of mines (one in Colorado and several in Illinois) had adopted the use of rock dusting or rock dust barriers, and only to a limited extent.

Several of the operators in Illinois reported using the rock dust barriers and that their use had prevented numerous coal dust explosions started by methane ignitions or blown out shots, "…from propagating beyond the barrier in the mouth of the panel in which the explosion originated"[12]. Additionally, it also discusses the possibility of lung damage from using rocks containing high percentages of silica for the rock dust product.

A new document released by the Bureau of Mines in 1927 reported on the modifications to the testing facility and the coal-dust explosion testing performed at the BEM between 1919 and 1924. The testing compared the standard that had been used for all previous testing, coal dust from the Pittsburgh seam, to coal dust from other mines, coal seams, coal-producing regions, and coal types. Within this report the Bureau of Mines published a table of the Limits of Explosibility of Coals Tested. In addition to listing the explosibility results of each coal tested, it "…presents valuable computations of the percentage of incombustible required to prevent ignition of or propagation of an explosion through various mixtures of coal dust and rock dust"[13]. This table indicated that no ignition could occur with any of the coals at a 64% incombustible content or above.

Attached as an appendix to the Bureau of Mines report (1927) are recommended procedures for rock dusting American coal mines to prevent coal-dust explosions. This attachment discusses and outlines the particulars of using rock dust in coal mines. The attachment details which mines should be rock dusted (listing bituminous or lignite coal mines unless kept in a "muddy" condition). As well as, specifics on the qualities and type of dust used (>25% quartz or free silica), the size of dust used (100% by weight passing 20 mesh and 50% passing 200 mesh), and the amounts of dust to be used (maintain 55%

incombustible content in all areas, increasing by 10% for each additional 1% of methane). Details for rock dust barriers were also given (>100 pounds of rock dust per square foot of entry cross section at barrier location). The parts of the mine to be dusted are also discussed (on the floor walls and roof of all main haulages, entries, and room and pillar workings to within 40 feet from the face or last cut-through). Finally, some comments on the sampling of the dust and maintaining of sampling records is covered[13]. This was the first document published in the United Sates that clearly spells out the risks of explosion and the benefits of rock dust in various types of coal mines across the country. However, due to the limited authority of the Bureau of Mines at the time, many still saw this information as suggestive or advisory.

The Bureau of Mines quickly followed this three-page rock dusting best practice guide with a 149-page document titled Safety in Coal Mining [A Handbook] in 1928. As its name implies, it was meant to be a "…concise statement of practices and methods recommended by the bureau for the increase of safety in coal mining"[14]. It did not introduce any new research or information, but was an attempt to get the information out to all of the coal mining industry. This was done so all in the industry had the same information regarding the causes and methods of prevention of coal mine explosions and other lesser hazards.

There were several topics discussed relating to the prevention of explosions. First was the use of ventilation to prevent gas buildup. This was followed by the explosibility risks of coal dust and rock dusting as a preventative measure. Two sets of standards were listed for rock dusting: the tentative specifications of the Bureau of Mines and the American Engineering Standards Committee's code of recommended practices. It is stated within that the code is the “same in principle” as that recommended by the Bureau of Mines, and that they “…cover different details but are in harmony with one another”[14]. It is of note that within the Bureau’s specifications, rock dust barriers are listed as an additional measure of safety to be installed “…at the mouths of all panels, cross-entries, and other key positions”, as suggested in the Bureau’s Technical Paper 84[14]. Additionally, the bureau engineers recommend that the barriers “…not be regarded as sufficient by themselves or as the most important feature”[14]. Furthermore, they state that “general rock dusting is more important”, and restate that barriers are only to be considered as a second line of defense[14]. Similarly, the watering of coal dusts is condemned as a sole means of prevention.

After the lengthy discussion on the explosibility of coal dusts and the standards for rock dusting, was a summary of facts regarding explosions and prevention. This section was very condensed and in plain language. Its purpose was to dispel some common myths long held in the coal industry regarding coal dust, methane, watering, etc. Next, the sources of ignition were discussed. Of primary concern were use of explosives, mine and miner lights (both safety lamps and the newer electric lamps), and electrical machinery[14]. The document was the first of its kind released in the United States by the government. The distribution of the information contained had far-reaching impact as is evidenced by the reduction in mine explosions and deaths the next year. In 1929, mine explosions only occurred 6 times and resulted in 146 deaths, an incredible reduction of the previous year (14 disasters/326 deaths in 1928)[3].

Attention returned to explosion prevention and the testing of rock dust barriers with the Bureau of Mines’ release of Bulletin 353 in 1932. By this time, rock dust barriers were being used extensively in coal mines in the United States, France, and Germany for the arrest of coal dust explosions[15]. In the few years since their inception into practice, many derivations on the basic principle of the rock dust barrier had been devised by mining men and placed into practice in their respective test facilities or mines. Unfortunately, many of these barriers were not designed on proper principles of operation and with little regard for sufficient amounts of rock dust capacity. Additionally, many mines were using these barriers in place of general rock dusting instead of supplementary to it. In cases where explosions occurred, these barriers often worked to stop the flame of an explosion, but did not prevent the death of those miners that were in the path of the flame or encountered the toxic gases resulting from an explosion, known as afterdamp[15].

In response, the Bureau of Mines performed systematic testing of about 350 barrier designs that showed a reasonable chance of success and were not cost prohibitive[15]. The significance of this research is in the determination of favorable qualities for proper barrier operation in wide-ranging explosion pressures, the effects of various construction and installation techniques, and the minimum requirements for rock dust loading. The testing resulted in three barrier designs being approved for general use, with four additional barrier designs approved for special purposes. The minimum requirement for rock dust loading was also lowered from 100 to 60 pounds per square foot of cross section area at the barrier location. This previous higher amount was utilized before general rock dusting became practice, and the lower amount is contingent upon proper general rock dusting[15].

Many other barrier specifics were determined and outlined in this research as well. These include the importance of a sturdy and rigid construction for proper operation. Additionally, barriers must extend across the entire width of the entry and be constructed close to the roof so flame does not pass over or around them. Furthermore, distance from the ignition source can affect proper operation if the barrier is too close for the explosion to develop adequate force to initiate the barrier before passing it. The ideal distance was not determined in this testing, but a preliminary distance of 200 to 300 feet was set[15]. In all, this research validated the efficacy of various barrier designs and detailed those qualities proven to be important for proper operation of any barrier.

In 1933, the Bureau of Mines released Bulletin 369 Explosion Tests of Pittsburgh Coal Dust in the Experimental Mine 1925 to 1932, Inclusive. This research was mostly a compilation of previous testing that focused around the tabulation of the effects of small changes to various factors of the coal and rock dusts used, the location and sources of ignition, and the varying distribution of coal dusts. Additional testing included the minimum gas explosion required to ignite coal dust and the effect that stratified gas mixtures had on ignition[16]. In general, this assisted in the understanding of the finer points of the ignition and propagation of coal dust explosions and the effects of various qualities of rock dusts in extinguishing a developing explosion. Research continued in this area of finer understanding, but with the declining occurrence of mine explosions and little new developments, safety regulations remained advisory[11].

This prior research and several larger headline-grabbing mine explosions led to many legislative changes over the following decades. After only 1 coal mine disaster in 1939 claiming 28 lives, 1940 brought 6 explosion disasters claiming 276 lives[3]. This promulgated Congress to pass Public Law 77-49 granting federal mining investigators the right of entry into private coal mines for the purpose of making inspections and recommending improvements[4]. Another large coal mine explosion disaster early in 1947 at the No. 5 mine in Centralia, Illinois, claimed the lives of 111 miners and instigated Congress to pass Public Law 80-328 creating the first Federal standards for safety in lignite and bituminous coal mines. This law also enhanced the rights of federal inspectors to notify mine operators and their respective state mining agencies of any violations, yet still no enforcement powers were afforded to any agency, state or federal, to ensure adherence to the new standards[4]. In 1951, the explosion at the Orient No. 2 mine in Illinois claimed the lives of 119 miners and prompted the implementation of the Federal Coal Mine Health and Safety Act the following year. This new law called for the discontinued use of black powder as an explosive, which was possible due to the discovery that the addition of sodium chloride to explosives reduced their flame production and thereby advanced permissible explosives. Additionally, the new law established rock dusting standards for all mines, requiring a minimum incombustible content of 65%[17]. This value is presumably derived from the Bureau of Mines' previous publication, Bulletin 268[13].

Seeing that the new laws had little impact on the continued occurrence of coal mine explosions through the remainder of the 1950s and into the 1960s, Congress expanded the Federal Coal Mine Health and Safety Act of 1952 to include all underground coal mines, not just those employing more than 15 people in 1966. The expansion also gave inspectors the right to issue withdrawal orders to mines that were repeat offenders refusing to comply with the new standards. Education and training programs for investigators and miners alike were also expanded[4]. In 1968 the Consol No. 9 explosion in Farmington, West Virginia killed 78 miners. With renewed interest in mine safety, the subsequent year brought the Federal Coal Mine Health and Safety Act, commonly known as the Coal Act. The most significant aspect of this new law was the ability for the federal agency to enforce safety standards with mandatory monetary fines and possible civil or criminal litigation. In 1973 the Mining Enforcement and Safety Administration (MESA) was created to relieve the Bureau of Mines from conflicting duties[4].

Another important event in 1973 was the release of the book Coal Dust Explosions and Their Suppression by a Polish researcher, Waclaw Cybulski. This nearly 600-page book is the first and only university-level collection and discussion of the worldwide research efforts and knowledge, to date, related to coal dust explosions, and their prevention and suppression. In addition to the collective knowledge base, Cybulski added results of research and experiments completed at the Polish Experimental Mine Barbara and compared them to those of the other researchers. Of significance to this report, are the findings by Cybulski of the explosibility of coal dusts based on the percentage of incombustible content needed to prevent the ignition of coal dusts versus that required to prevent the propagation of an explosion. Cybulski concluded from his research that under the most ideal conditions, incombustible contents of up to 82.5% were required to prevent the propagation of an explosion due to the strong turbulent movement of particles within the dust clouds[18]. This was much higher than the 60 to 65% incombustible content currently required to prevent the ignition of various coal dusts. Additionally, Cybulski found that coal dust explosions can be initiated with less energy in smaller workings, like roadways, yet an explosion that has already developed propagates more easily in a larger working.

Among his many conclusions, Cybulski states that it is not possible to fight the coal dust explosion hazards found in most coal mines by just one method, and that in the fight against them "…not a single line of defense can be neglected"[18]. Furthermore, he states that in spite of the complex nature and various causes of coal dust explosions, the task of overcoming them is practical and attainable if all lines of defense are utilized[18]. Cybulski listed nine practices of paramount importance in the prevention and control of a coal dust explosion. The following is a brief explanation of his points:

1) Limiting the formation of coal dusts: this applies to the means by which coal is extracted, and to the fineness of coal dust produced during the mining operations.
2) The removal of coal dusts: this refers to good housekeeping practices of preventing and removing spills and other accumulations, and the use of dust collection equipment where appropriate.
3) Preventing the dispersibility of coal dusts: this is typically done by wetting of the dust to keep it from floating on the air currents in the mine. This is generally done at the point of formation, such as the cutter head of a continuous miner, or at points where the dust can be raised into the air, such as at dumps, transfer and discharge points, and along haulageways due to the passing of equipment.
4) Preventing the ignition of the primary dust cloud: this refers to reducing the ignitability of the coal dust (by increasing incombustible content or wetting), and the control of ignition methods (open flame, electrical arcing, explosives use, friction, and methane ignitions)
5) Restraining the development of coal dust explosions: this directly relates to rock dusting practices.

6) Limiting the range of coal dust explosions by stunting the progress of the already developed explosions: this relates to the necessary use of explosion barriers.
7) Checking up on the hazards of coal dust explosions: this means to periodically re-inspect and re-evaluate the hazard.
8) Issuing regulations on suppressing the hazard of coal dust explosions: this calls on the governments of coal mining nations to enact safety regulations based on scientific research.
9) Carrying out scientific research work on the improvement of methods of suppressing coal dust explosions: this calls for the continuation of future research into this area.

In support of his reasoning for these nine lines of defense, Cybulski admits that any one of them "…might, unfortunately, fail now and again…" within the dynamic working environment of a coal mine allowing the initiation of a coal dust explosion[18]. His viewpoint on the inevitability of future explosions is due to his belief that the rock dusting standards of many other countries "…are in many cases inadequate"[18]. The extent of damages related to any explosion is in direct relation to the intensity of the explosion, which in turn depends on various parameters, not the least of which is the distance an explosion is allowed to continue. Cybulski states, "…therefore it is most desirable to ensure that its course be made as short as possible"[18].

Cybulski further highlights the importance of stone dust barriers at arresting coal dust explosions by stating that they are "…to be used as the last defense line", and that they are "…of the highest possible dependability for checking the range of an explosion"[18]. Over 1,700 tests were performed at the Polish Experimental Mine Barbara on explosion barriers of various types and construction, and of those utilizing stone dust and water. Testing there determined both extinguishing media to be satisfactory at stopping medium to strong explosions, while the stone dust barriers had a slight advantage at stopping weaker, slower traveling, explosions. Testing also determined the ideal barrier placement for the three degrees of explosion intensities were all at 100 meters; while Cybulski states that “barriers placed at distances from 60 to 200 meters from the gallery’s face stopped explosions assuredly, in all cases”[18].

While this research was not performed in the United States, it had a large impact on the scientific community in the United States after its translation to English and subsequent publishing of the complete work for the Bureau of Mines was completed in 1975[18]. The following year, the Bureau of Mines released the Report of Investigations 8170 titled “Water Barriers for the Suppressing of Coal Dust Explosions”. After testing three different designs of water barriers in a single entry at the Bruceton Experimental Mine, researchers proposed plans for the implementation of water barriers in a working mine on a trial basis[19]. In 1977, the Federal Mine Safety and Health Act was passed. This act consolidated all of the Federal health and safety regulations related to mining of any kind under one law and authority, the Mine Safety and Health Administration (MSHA). This act also required rock dusting of return air to be increased to 80% incombustible content as opposed to all other applicable locations requiring 65% [20].

The year 1981 saw the final testing of coal dust explosion related research at BEM, with the release of Report of Investigations 8538, titled “Suppression of Coal Dust Explosion by Water Barrier in a Conveyor Belt Entry”. This was a continuation of the 1976 work by the Bureau of Mines, and was a realization of the recommendations made therein to test the water barriers in a belt entry[21]. With the funding set out in the 1977 Mine Safety Act, the Bureau of Mines acquired a 400-acre facility to continue research in a larger, multiple-entry mine setting, and in 1982 the Lake Lynn Experimental Mine was opened. Much of the focus of research there was related to self-rescuers, oil shale mine explosion risks, explosives, and mine seals and stoppings[11].

In 1995, Congress recommended the closure of the USBM to the chagrin of many in the industry. The mining research laboratory facilities and staff were temporarily transferred to the Department of Energy, but after a few months landed under the supervision of the National Institute for Occupational Safety and Health (NIOSH), under the Centers for Disease Control (CDC). To date the Mine Health and Safety program has maintained a separate identity within that of NIOSH[22].

2.5. CURRENT COAL DUST EXPLOSION PREVENTION STRATEGIES WORLDWIDE

In coal mining countries around the world, there are four primary strategies employed to manage the risk of coal dust explosions and their widespread damage. There are multiple control strategies because no single prevention or control measure is sufficient by itself and can easily break down or fail in mining conditions. Similarly, different mines, and different locations within the same mine, can require different control approaches. The need for each strategy rests on their individual merits, but the individual strategies work together to form a mesh of protective measures that is only as strong as the weakest layer.

The first, and most effective, coal dust explosion prevention strategy is the removal of any coal dust accumulations. This prevents coal dust accumulations at transfer points and along coal transportation routes. The cleanup of any spill or accumulations of coal dusts within the mine should be performed. However, this is not always possible, or safely practical, such as in the return airways.

The second coal dust explosion prevention strategy is the wetting of the coal dust to prevent it from becoming airborne, stoichiometrically mixed, and capable of being ignited. This is typically done where the coal dust is produced, near the cutter or shearing heads of the mining equipment. Modern coal mining equipment can be outfitted with water sprayers and/or dust filtration systems. However, this is not always possible or practical throughout a working mine.

The third coal dust explosion prevention strategy is to mix the coal dust with an inert material. Typically, limestone dust is used, giving rise to the action known as rock dusting or stone dusting. This effectually increases the total incombustible content (TIC) of the dusts that collect in the mine workings. These dusts could become airborne and ignited in the event of an explosion if the TIC of the dusts is not high enough. However, since coal dusts are continually produced during mining operations, rock dusting requires continual renewal.

The fourth coal dust explosion prevention strategy is the installation of an explosion-activated barrier that is comprised of a sufficient quantity of inert material, which when released makes an entire section of the mine entry inert and incombustible. This acts to interrupt the progress of the flame front of a developing explosion, so it cannot continue propagating into the next section. The two main sources of coal dust ignition and its subsequent explosion are small methane gas ignitions and improper use of explosives. These sources of coal dust ignition are controlled via separate means and regulations but also play an integral role in preventing coal dust explosions.

2.5.1. U.S. Mines and Their Current Practices. As per the Code of Federal Regulations (CFR) Title 30; Part 75; Subpart E-Combustible Materials and Rock Dusting; Section 75.400 through 75.404, and in summary:

- Coal dust, coal float dust, loose coal, and other combustible materials shall be cleaned up and not permitted to accumulate in active workings or on equipment therein
- A program for regular cleanup and removal of these items shall be established and maintained
- Where mining operations create or raise excessive dust, water (with or without wetting agent) shall be used to abate such dust, with distances less than 40 feet from the working face, water (with or without wetting agent) shall be applied to ribs, roof, and floor to reduce dust dispersibility and minimize explosion hazard
- All underground areas of mine, except those areas where the dust is too wet or has an extremely high incombustible content, shall be rock dusted to within 40 feet of all working faces, including crosscuts, unless deemed unsafe to enter
- Where rock dust is required, it shall be distributed on the top, floor, and sides of all underground areas and maintained in such quantities that the total incombustible content of the coal dust, rock dust, and any other dust or moisture shall be not less than 80%.
- Where methane is present the percent of incombustible content of the combined dusts shall be increased 0.4% for each 0.1% of methane

The MSHA standards address three of the four coal dust explosion prevention strategies, coal dust removal, coal dust wetting, and mixing of coal dust with inert material, or rock dusting. However, the MSHA standards do not address the fourth coal dust explosion prevention strategy of explosion activated barriers[24].

2.5.2. Foreign Mines and Their Current Practices.

While there are many countries that mine coal and that have implemented coal dust explosion barriers into their regulatory regimes, finding English translations of those regulations was difficult. Therefore, attention was focused on those regulations that could be readily obtained in English, such as; Canada, New South Wales (NSW), New Zealand (NZ), the Republic of South Africa (RSA), and the United Kingdom (UK). While there were minor differences in the required percentages of incombustible content for these countries (between 65% and 85% in certain areas[25]), they all detailed similar strategies for the prevention and removal of coal dust buildups, wetting of coal dusts in areas with high ignition probability or high dust production to reduce explosion hazards, rock dusting to within 12 meters (40 feet) of the working face on all surfaces, and increased rock dusting requirements for the presence of excess methane (from 0.4% per 0.1% methane to 1% per each 0.1% methane)[26- 33]. However, unlike the U.S. CFR, all of these foreign regulatory regimes require the implementation and maintenance of explosion activated barriers as part of their explosion prevention and suppression tactics.

In Alberta Canada, regulations require the design, erection, location, and maintenance of explosion barriers is certified by a professional engineer. Additionally, they must be placed at all entrances for every production section, all entrances to every development district (as soon as the development district has advanced 200 meters), and at all entrances to every ventilation split (intake and return)[25]. In British Columbia Canada, any underground coal mine that is dry and dusty must have explosion barriers certified by the chief inspector. The barriers are to be installed at locations designated by the manager and authorized by the district inspector. Regular inspections (every 4 weeks or less) and inspector qualifications are also stipulated[25]. In New Zealand, mine employers must take practical steps to ensure that explosion barriers are erected at suitable locations that will limit or contain the ignition of coal dusts or gases[31].

In NSW, mine managers are required to have means in place to prevent an explosion and to suppress any such explosion should it occur, including but not limited to prevention of coal dust accumulations, required amounts of stone dust applied, and the installation and maintenance of explosion barriers[33]. A separately published technical document spells out the required locations and other barrier requirements[32]. Additionally, companies such as Skillpro Services in NSW, who were invaluable sources of information for this project, have published guidelines for the implementation of their bag barrier systems in mines[34].

In the UK, mine operators must ensure that suitable and effective explosion barriers are in place to prevent the development and propagation of a coal dust explosion[29]. Again, separate technical documents dictate the location and other requirements of the barriers[28]. Finally, in the RSA, mine employers must ensure that effective measures are taken to prevent or suppress coal dust explosions[27]. There is also an entire document devoted to guidelines and codes of practice for the prevention of coal dust explosions, including prescriptions for explosion barriers and their installations[26].

In review of the separate explosion prevention documents for the RSA, UK, and NSW, it was noted that all three outline descriptive and installation requirements of a bagged type of stone dust explosion barrier. Many other similarities were also noticed. The similarities and differences in barrier specifications are best summed in the Table portrayed in Figure 2.2.

2.6. STONE DUST BARRIER HISTORY, DEVELOPMENT, AND TESTING

Stone dust explosion barriers were initially introduced in the 1920s and consisted of elevated shelves that supported mounds of stone dust on them. The basic design principle was that the pressure wave that moves ahead of an explosion flame front would upset, or overturn, the shelves causing the supported stone dust to become airborne and extinguish the flame front upon its arrival due to the high levels of incombustible content. Their design did not change much over the next decades, except for slight variations in the construction of the shelves, the materials used for shelf construction, and the amount of stone dust supported on them. A variant of this basic design was also developed using troughs of water instead of stone dust[33]. Regardless, explosion barrier use was still limited even after the most recent research completed at the time, performed by Cybulski in 1973, clearly showed that stone-dusting alone was not sufficient to prevent or suppress coal dust explosions, and that additional lines of defense, such as explosion barriers, were needed[18]. This echoed the same advice of George Rice's experiments in the early 1900s.

In the early 1990s the Division of Mining Technology within the Council of Scientific and Industrial Research (CSIR) of South Africa began development and testing of a new system for the effective implementation and low cost installation of stone dust barriers[35, 36]. This was conducted in response to recent mine explosion disasters there,

Figure 2.2: Comparison of Bagged Stone Dust Barrier Specifications for the United Kingdom, Republic of South Africa, and New South Wales[35]

and the need for a system that was effective, yet cheaper and easier to install and maintain. This new system was based on individual bags, containing stone dust, hung in an equal distance and spacing arrangement from the mine roof, known as the bag barrier. The bags would react to an explosion, much the same as the previous shelf designs, and disperse the contained stone dust (Figures 2.3 and 2.4). The bags themselves are designed with special anisotropic characteristics that support the weight of 6kg (approximately 13 pounds) of stone dust for an indefinite period of time without deteriorating or degrading, and still rupture at very low pressures (reported as low as 4.0 kPa or approximately 0.58 psi) allowing dispersal of the enclosed stone dust[36]. Furthermore, the bag and complimentary hook and ring closure system effectively encloses the stone dust, aiding in the prevention of moisture contamination and caking of the stone dust (Figure 2.5.).

Figure 2.3: Bag Testing in Shock Tunnel at Kloppersbos Testing Facility

The bag and hook design underwent extensive testing and development over the next several years. The testing continued at the Kloppersbos Research Facility in South Africa (a circular tunnel with 5m2 cross sectional area) and the Tremonia Experimental Mine Gallery in Germany (20 and 22 m2 cross sectional areas). This testing proved the concept of the bag stone dust barriers, and the effectiveness of these barriers at protecting long single-entry mines during coal dust explosions of varying magnitudes. However, most underground coal mines use multiple entry methods of mine development.

Figure 2.4: Bag Explosion Testing at Kloppersbos Testing Facility

Due to the common use of multiple entry mining layouts, further testing was performed at the National Institute for Occupational Safety and Health (NIOSH)

Pittsburgh Research Laboratory's Lake Lynn Experimental Mine in Pennsylvania in the late 1990s[36]. This facility was the only one worldwide that could accommodate such explosion barrier testing in a multiple entry development. The test facility was comprised of three entries with seven crosscuts located towards the inby end of the entries. This layout is similar to three entry headings currently used in many U.S. longwall coal mines. After several preliminary test explosions were performed to calibrate the equipment and explosion pressures, the bag stone dust barriers were tested in various barrier configurations and under various explosion pressures.

Figure 2.5: Stone Dust Filled Bag and Hook Hanging from Test Stand [35]

In these tests, the bagged stone dust barriers were proven to be 100% successful, in the distributed barrier and concentrated barrier configurations, at stopping the flame propagation of a coal dust explosion within the barrier zones under different coal and stone dust loading amounts (69 and 82 percent TIC)[36]. This testing therefore proved the viability of using the bagged stone dust barriers in medium, multiple entry mines under different dust loading and barrier configurations. However, the bag barrier system's operation is still dependent on the pressures developed by the explosion and the barriers' location in respect to the ignition point (bags located in crosscuts are less likely to rupture and disperse stone dust effectively due to pressure equalization between entries)[36]. Based on these findings, the RSA and NSW began outlining the use of bagged stone dust barriers in their regulations in 2002, with the UK following suit in 2004[37-39]. Furthermore, many countries' principle barrier design features are based on the distance, spacing, and dust loading outlined in these conclusive tests.

A bagged stone dust barrier was reported to have been activated during an explosion in an underground Polish coal mine in 2002. The explosion was caused by the incorrect use and disposal of explosives. It was reported that ten miners inby the barrier were killed. However, two miners located just outby the barrier were burned but survived, and thirty-five miners in an adjacent longwall panel were unharmed[40]. So, thirty-seven lives were saved in this instance by the use of the bag stone dust explosion barrier system.

2.7. HIGH EXPLOSIVES TESTING

When a spherical high explosive charge detonates, energy is released from the chemical bonds and the resultant hot gases quickly expand outward, spherically, from the charge. This sudden expansion of hot gases lasts only a few microseconds. The amount of gas produced is relative to the chemical composition of the explosive itself, and the pressure imposed by the expanding gasses is dependent on the position, or distance from the detonation, that the pressure observation is made. In cases where the detonation occurs in a large open space, commonly referred to as a free-field blast, the hot gas production results in the rapid expansion of the surrounding air, further propagating with wave-like behavior. This means that the shock wave created from the detonation transfers energy through matter and space without a transfer of mass. This shock wave produces a nearly instantaneous rise in pressure surrounding the charge that propagates through the air with a velocity greater than the speed of sound. The highest pressure attained is denoted as the peak pressure; and the time elapsed from the arrival of the pressure wave to the peak pressure point is called the pressure rise time. After the shock wave reaches its maximum pressure, the pressure begins decreasing exponentially until it equals the ambient air pressure; this period is designated as the positive phase duration. Following this, the pressure surrounding the detonation becomes lower than ambient air pressure for a brief period, called the negative phase. The negative phase of the shock wave has a longer duration waveform than that of the positive phase; which exhibits high intensity and short duration. This comparison can readily be seen in Figure 2.6. Furthermore, the area under the time pressure curve in Figure 2.6 represents the impulse of the detonation event. The short duration of the peak pressure spike compared to the overall duration of the positive phase indicates that the time required to rupture a barrier bag and disperse the contained stone dust is likely related more closely to the impulse than the peak pressure. Additionally, as the distance between the charge detonation and the point of pressure measurement is increased, the positive phase duration increases and the peak pressure decreases[42]. Figure 2.7 illustrates the effect that distance has on the lowering of peak pressures and the lengthening of the positive phase.

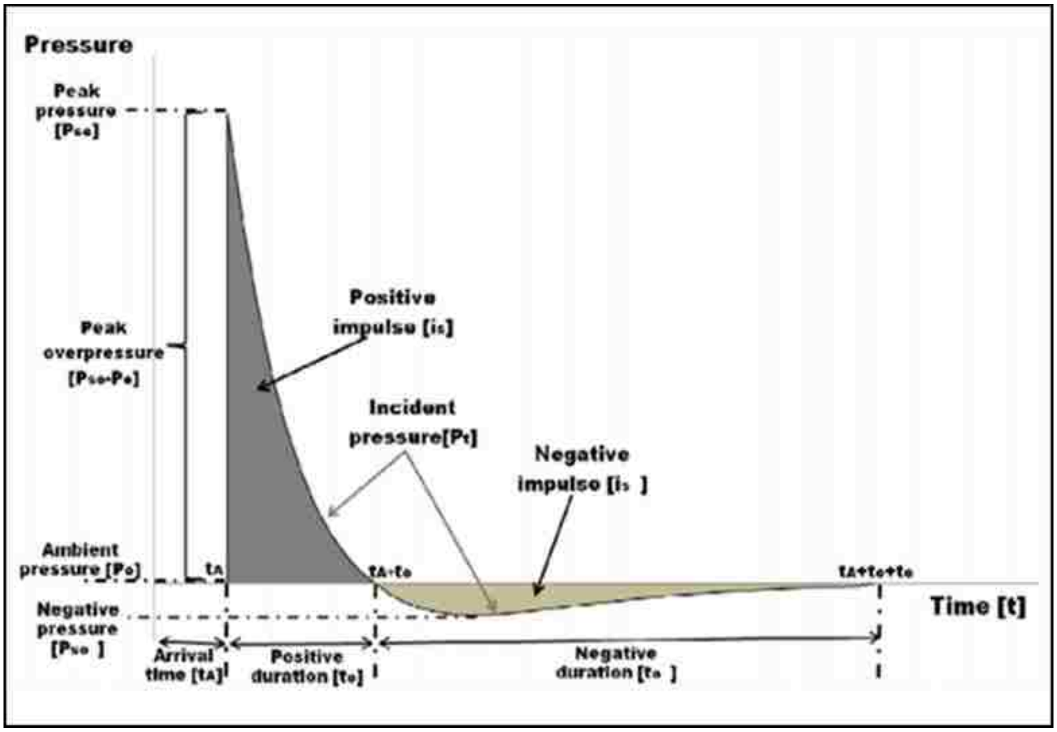


Figure 2.6: Pressure vs Time Graph[43]

Regarding explosion pressures, there are differences in the way explosion pressure is applied to objects, and therefore also differences in how pressure is measured. Hydrostatic, or incident, pressure is measured by a sensor mounted flush to a surface that is parallel to the flow of the blast wave. This pressure indicates the force (per unit area) on a surface caused by the motion of the air/gas molecules around it, but does not include any translational kinetic forces from that gas[44]. Reflected pressure is due to the gas

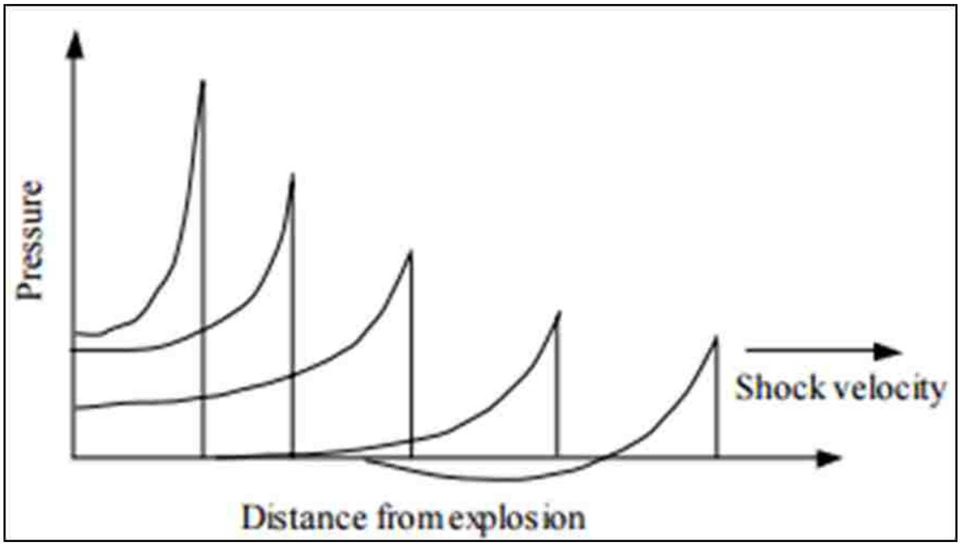


Figure 2.7: Pressure-Distance Relationship[42]

behind the shock being "…brought to rest non-isentropically" against a surface that is face-on with the blast, and adds the translational kinetic energy component to the hydrostatic pressure measurement[44]. Reflected pressure is the biggest load force produced by an explosive wave. Total pressure, or stagnation pressure, is the pressure that remains after the primary shock reflects back into the oncoming blast wave, and is measured by a sensor mounted flush to a surface which faces the flow of the blast wave. This results in a value that represents the pressure exerted on a surface by the work done to "…bring the gas to a rest and to compress it adiabatically"[44]. Dynamic pressure is not a physical property of the flow from a blast wave and cannot be directly measured. It can however be calculated from the simultaneous independent measurement of hydrostatic and total pressures[44].

The measurement of total and hydrostatic pressures can be performed with sensors that utilize piezo-electric crystal technology to produce a high response rate electrical signal. This signal is very low current and requires a signal amplifier in-line or built into the data storage device. The range of electrical voltage supplied by the sensor is calibrated to a pressure curve supplied by the sensor manufacturer. Hydrostatic pressure sensors are typically mounted in the side of a sharp pointed cylinder, called a pencil probe (Figure 2.8). The point is directed at the center of the charge to minimize edge effects from the shock striking the transducer at an angle[44]. Total pressure sensors, sometimes called surface mount sensors, are similar except the piezo crystal faces the blast wave and is recessed in the end of a threaded body (Figure 2.9).

Figure 2.8: PCB Piezotronics Pencil Probe Pressure Transducer[45]

Figure 2.9: PCB Piezotronics Surface Mount Pressure Transducer[46]

The characteristics of a given blast wave are of interest in various explosives research areas such as structural design, weapons design, and injury prevention and characterization, just to name a few. The pressure rise time is one parameter to consider in blast wave pressure analysis. In a theoretical shock wave the rise time is considered to be zero. However, in reality there is a finite, yet extremely small, amount of time that passes during the pressure rise. The positive phase duration can be calculated by subtracting the wave arrival time from the positive phase end time, shown in Formula 1. The positive phase duration is important in understanding the magnitude of force applied on an object or structure because it directly affects the impulse of the shock wave. The impulse is a quantitative measurement of the magnitude of pressure applied over a specific amount of time, and greatly influences the degree of damage to an object or structure, or the extent of injury to a human being exposed to an explosion shockwave[42]. By definition, impulse is the area underneath a pressure-time graph; or in other words, the integral of pressure as a function of time from the wave arrival time (t_a), to the time that the positive phase ends (t_a+t_{pp}). This definition is shown in Formula 2. Since a pressure curve cannot easily be represented with a mathematical function, impulse is often calculated via a finite sum method, or slicing method, as shown in Formula 3. In this method, the average of two pressures in successive time slices is multiplied by the difference in their corresponding times, and then the products of all the slices are summed.

Formula 1: *Positive Phase Duration = Positive Phase End Time - Wave Arrival Time*

Formula 2: $Impulse = \int_{t_a}^{t_a+t_{pp}} P(t)\,dt$

Formula 3: $Impulse = \sum_i^n \frac{1}{2}(P_i + P_{i-1}) \times (t_i - t_{i-1})$

Often, pressure and impulse are analyzed together in order to determine the amount of damage caused by explosives and their subsequent shock waves. By plotting the peak pressure and maximum impulse of a blast on an object-specific pressure-impulse diagram, such as the one pictured in Figure 2.10, the threshold of damage caused by the pressure and impulse components of explosions can be established. The perpendicular lines with a radiused corner depicted in Figure 2.10 represent the damage threshold for the object being tested, or the curve of constant damage. In the case of testing for this thesis, it will represent the bags, and it is the one variable that remains the same throughout the testing. To the left, or below, the curve of constant damage is a region of little to no damage, or inconsistent damage to the items tested. Above or to the right of the curve is a region of consistent and severe damage to the items being tested.

Another pressure-impulse diagram is depicted in Figure 2.11. However, this diagram shows more detail regarding the specific damage regions, and that region's sensitivity to impulse, pressure, or a combination of the two known as the dynamically sensitive region, which is typically the most difficult region to define. Note that the pressure and impulse axis are swapped between the two diagrams. If the sensitivity regions in Figure 2.11 are examined, it is noticed that as pressure decreases, the pressure sensitive region is entered. It is called this because very little differences in pressure require large changes in impulse to maintain the curve of constant damage. Conversely, as pressure increases, the impulse sensitive region is entered because very little differences in impulse require large changes in pressure to maintain the curve of constant damage. These asymptotic regions define the limits of the pressure and impulse effects on the objects being tested.

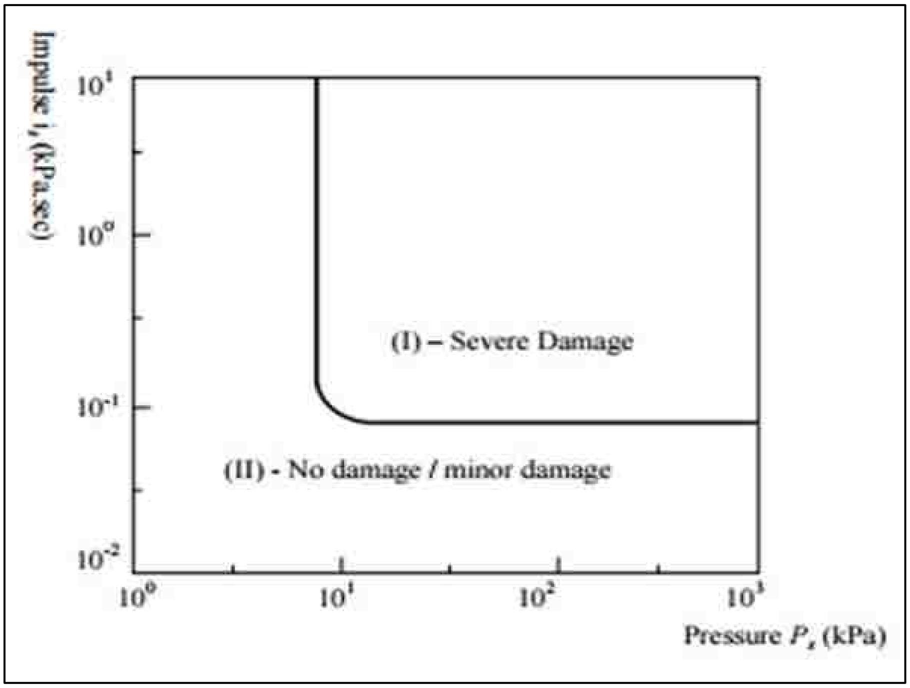


Figure 2.10: Pressure-Impulse Diagram[42]

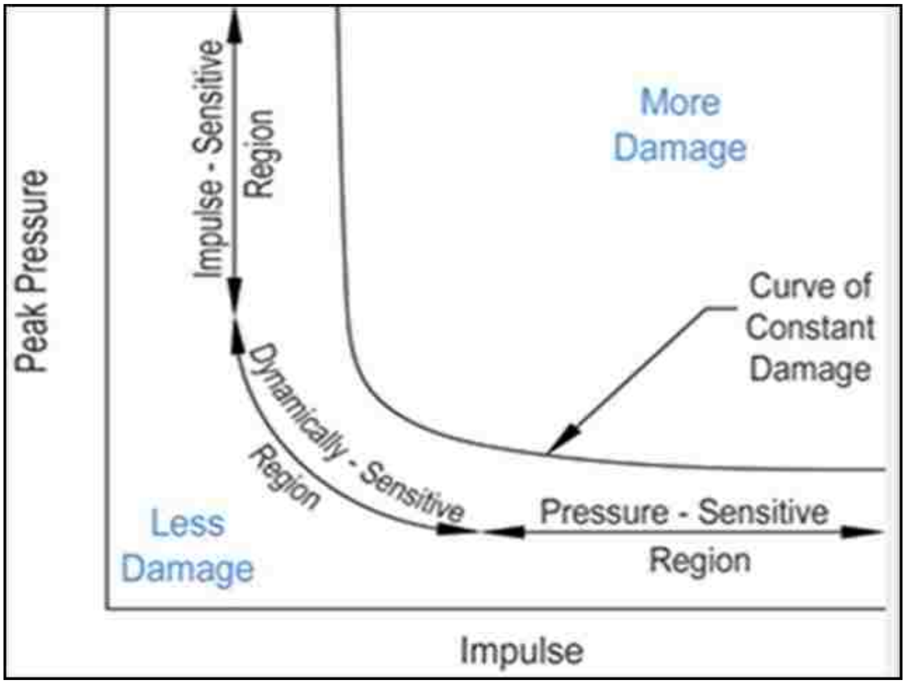


Figure 2.11: Pressure-Impulse Damage Curve with Sensitivities Labeled[51]

Deviations from an ideal pressure-time graph will add complexities to pressure data analysis. In most testing situations, the explosive charge is in proximity to objects and obstacles, such as walls or the ground, causing the shock wave produced during the explosion to be reflected off these surfaces. As the incident shock wave and reflections interact, they can act constructively and cause an increase in pressure and impulse[43]. This phenomenon is illustrated in Figure 2.12. Additionally, this causes the positive phase duration to increase due to the creation of multiple peaks in the pressure curve. This also leads to an increase in the explosion impulse. This can have a significant impact on the shock wave's effect on nearby objects and the resulting damages. A more realistic pressure-time graph with multiple reflections is typical of what would be expected to be witnessed during the explosive testing of the barrier bags, and is portrayed in Figure 2.13. The multiple reflections act to increase the explosion impulse without significant impact to the maximum pressure, similar to that observed in explosion shock tunnel testing and mine tunnel explosions.

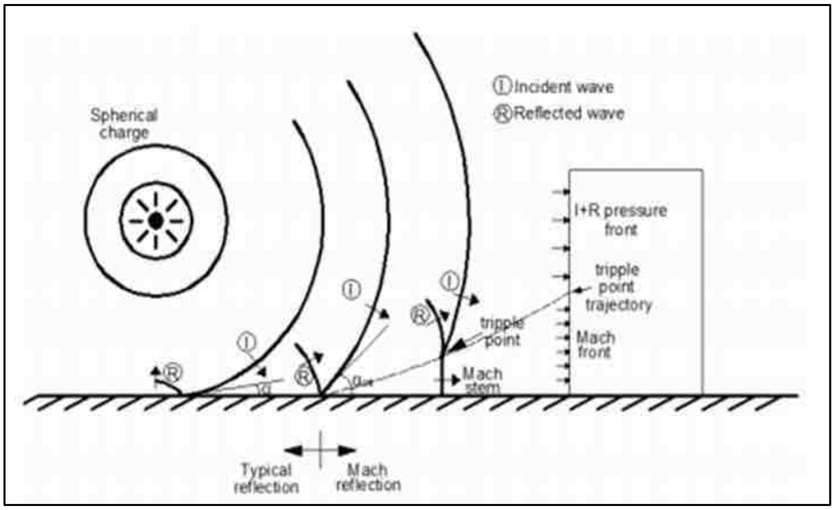


Figure 2.12: Interaction of Reflected and Incident Shock Waves[43]

The understanding of these explosives testing principles and parameters was imperative for the testing to later be performed on the barrier bags, and the resulting data analysis and conclusions. The distance effects on pressure and impulse, along with the pressure and impulse increasing effects of shockwave interactions are crucial to designing bag testing experiments so that the desired ranges of pressure and impulse are obtained in each of the experimental setups.

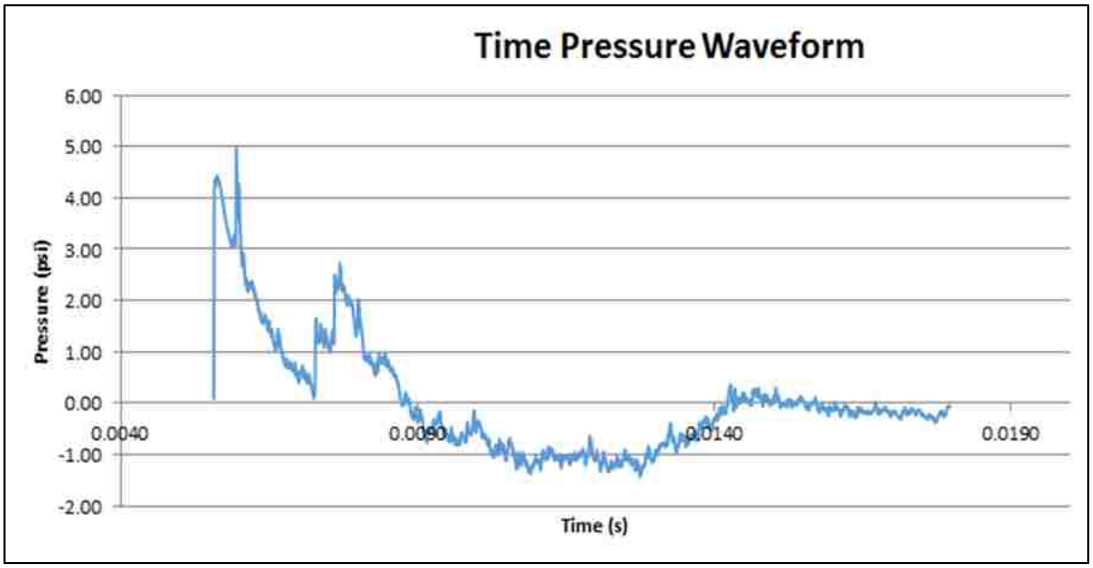


Figure 2.13: Realistic Pressure - Time Graph

2.8. SUMMARY

In conclusion, coal mining has been a part of American culture for over 300 years, even before its independence from Great Britain. Coal mine explosions have been occurring since the mines got deep enough that adequate ventilation to prevent methane buildup became a problem. There have been many methods used over the years to prevent coal mine explosions, early ones centered on eliminating methane accumulations by igniting them regularly. Later, scientific research lead to other methods of better ventilation, and the importance of ventilation on methane removal became clear. Further research led to the insight of the involvement of coal dust in coal mine explosions, along with the need for increasing the incombustible content of mine dusts. This insight led to the practice of widespread rock dusting. The occurrence of coal dust explosions was reduced drastically, but continued to occur. Continued research showed that rock dusting alone is not a guarantee against coal dust explosions and additional testing centered on explosion barriers. Many versions of barriers were developed and tested over the decades by researchers from numerous countries.

In response to continued coal dust explosions and increasing costs of prevention, researchers in South Africa developed a new type of explosion barrier, the bagged stone dust type of explosion barrier. Development of this system continued with testing performed at different research facilities around the world, including the Lake Lynn Test Facility in the United States. All testing in the various galleries proved this barrier type to be effective at extinguishing a propagating explosion. Based on the results of the testing, the RSA and NSW began to implement them into their mines. Regulatory agencies in, NZ and the UK soon followed. The United States has increased the TIC requirement of mine dusts, but has yet to institute the use of explosion barriers, though a century of research by a multitude of domestic and foreign researchers have shown that the practice of rock dusting is insufficient in and of itself to prevent the propagation of a coal dust explosion; and that additional methods of prevention are historically recommended, such as explosion barriers.

The explosive testing to be performed as part of this thesis is based on widely accepted understanding of explosion shock physics. Standard equipment and principles will be utilized to complete the testing. Common formulas will also be used to calculate values needed for the analysis and assessment of the peak pressure and impulse effects of explosion shock waves on the barrier bags. The difference between peak pressure and maximum impulse is significant to the understanding of the operational characteristics of the barrier bags, and their application within mine settings.

3. OPERATION OF BAG TYPE PASSIVE EXPLOSION BARRIERS

3.1. BAG BARRIER TESTING OVERVIEW

The purpose of investigating the operation of bag type passive explosion barriers (Objective 1) was to understand the principle operational characteristics of the system. This was needed so that nothing in the fundamental operation of the bag barriers would be overlooked in their application and implementation into the diverse and dynamic environments found in U.S. coal mines. A review of previous bag barrier system testing unveiled a discrepancy in previous testing and the possible misrepresentation of the dynamic operation of a barrier bag. Previous research reports the minimum pressure required to “operate” a bag barrier system is as low as 4.0 kPa (0.58psi)[36]. However, this research makes no distinction between the pressure required to rupture the bag, and the sudden rush of a large mass of air past the ruptured bag that is believed to disperse the contained rock dust. Both are required to extinguish a developing coal dust explosion; however, these two operational aspects are of different genesis.

A majority of underground coal mines are constructed of rectangular cross-sectional tunnels (similar to explosive shock tunnels). When an explosion occurs, the mine tunnel confines the gaseous bi-products and focuses the gases along the course of the tunnel away from the source of ignition. To demonstrate the importance of the explosion pressure funneling effect of the mine tunnels on the rupture of the barrier bags and the subsequent dispersing of the contained rock dust, the bags were tested in two different ways.

First, the bags were tested in an open air, or arena, testing environment to determine the minimum explosion shock pressure required to rupture or tear the stone dust filled bags without any influence from the pressure funneling effect of a mine tunnel. Second, the stone dust filled bags were tested in a fabricated steel shock tunnel to demonstrate the same range of explosion shock pressures found to rupture or tear the barrier bags in the arena tests, but with the added effects of increased impulse from the simulated mine tunnel. These tests should clearly demonstrate that the minimum explosion shock pressure required to rupture the barrier bags is significantly higher than referenced, and is separate from the impulse required to disperse the newly released stone dust along a mine tunnel.

3.2. OPEN AIR TESTS

This experiment consisted of 3 test shots, outfitted with 6 pressure sensors each, performed in an open arena. Each test was performed with incrementally larger C4 explosive charge sizes. The sizes of C4 charges for the three tests were 60 grams, 120 grams, and 240 grams. The recording of the resultant pressures, impulse, and the effects of the shock pressures on the Skillpro Stone Dust Barrier Bags was performed. The materials and equipment utilized during these tests are listed in Appendix A.

3.2.1. Open Air Testing Method. The goal was to record the pressure versus time data, to analyze the recorded data, and to determine the Time of Wave Arrival, Peak Pressure, and Positive Phase End Time. These values were then used to calculate the Positive Phase Duration and Impulse. The resulting damage, or lack of damage, to the barrier bags was also recorded. This allowed the assessment of the bags in relation to pressure and impulse, and set the target pressures for the tunnel testing.

Six test stands were fabricated to support the barrier bags by their mounting hooks and included pressure probe mounts that fixed the probes at the approximate center of mass of a 6 kg stone dust filled barrier bag so the pressure readings obtained accurately represented the pressure experienced by the bag. One Skillpro Stone-Dust Bag was hung from each test stand, approximately midway on the horizontal hanger bar as shown in Figure 3.1. The placement of test stands within the setup area was considered so that a view of all test stands was not obstructed from the camera located in the video viewing panel within the safety bunker. The charge hanging stand, with charge hanging wire, was placed in a central location. Measuring from the charge hanging wire, the first test stand was placed at a distance of 5 feet (Test Stand 1 in Figure 3.2). Each additional stand was placed at a 2-feet greater distance than the previous one, being sure not to position them directly behind the previous stand when viewed from the explosive charge position.

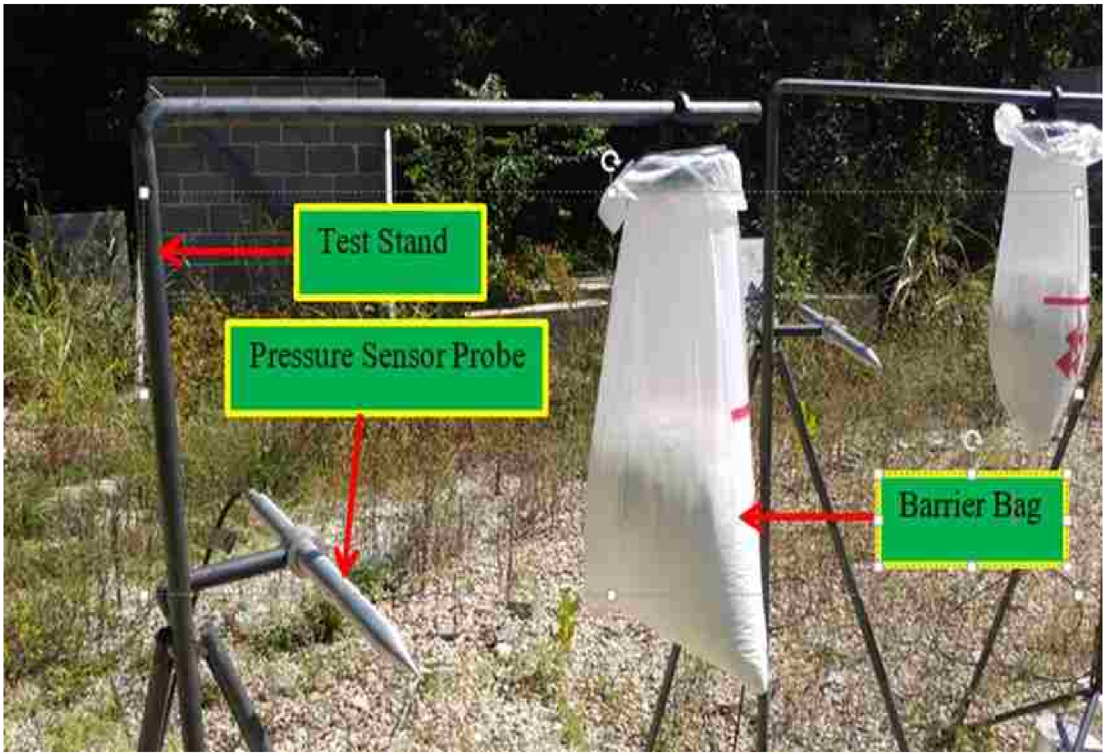


Figure 3.1: View of Typical Test Stand, Pressure Sensor, and Barrier Bag Setup

When complete, six test stands, arranged in an arc around the centrally located charge hanging wire, were used at distances of 5, 7, 9, 11, 13, and 15 feet. The pencil probe pressure transducers, measuring incident pressure, were inserted into the holders until the sensor crystal assembly was in line with the vertical bar of the stand, or centrally located with the bag. They were also verified to be angled directly at the center of the explosive charge and at the correct distance, and then secured. The probes were numbered 1 through 6 to resemble the corresponding barrier bag on the same stand. Probe 6 was in the final stand located at 15 feet, as shown in Figure 3.2. Pre-made weights were hung on each test stand for stability during testing.

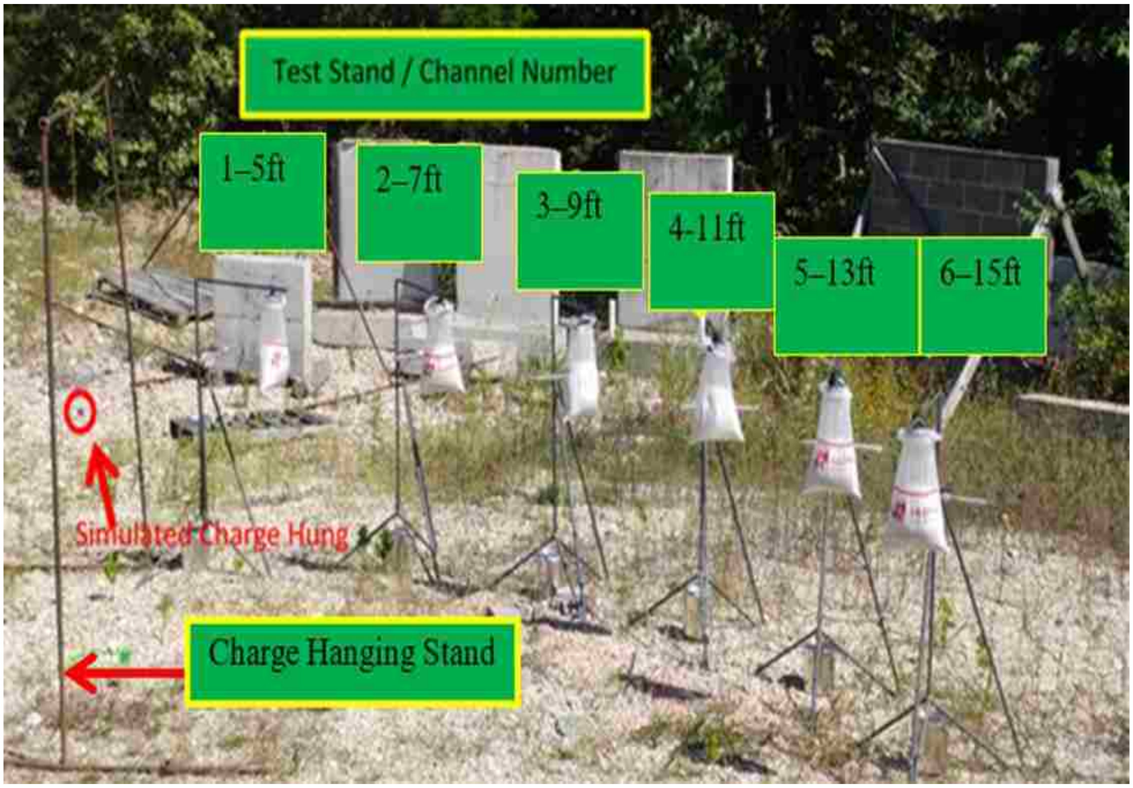


Figure 3.2: View of Test Site Setup Illustrating the Test Stand Order and Position about a Simulated Charge

A standard blasting cap was prepared with a trigger wire pigtail taped over the end so the pigtail wire would be broken upon detonation of the blasting cap. The wire breaking opens the trigger circuit signaling the time of detonation (T0) to the DAS. This data parameter was used for signaling the beginning of data recording. The desired size charge for the test being performed was hung from the charge hanging wire at the same elevation as the middle of the Skillpro Stone-Dust Bags, 4 feet from the ground. The blasting cap, with the trigger wire pigtail, was inserted horizontally into the rear of the hanging charge (the side facing away from the test stands and barrier bags), with the wires routed away from the charge as depicted in Figure 3.3.

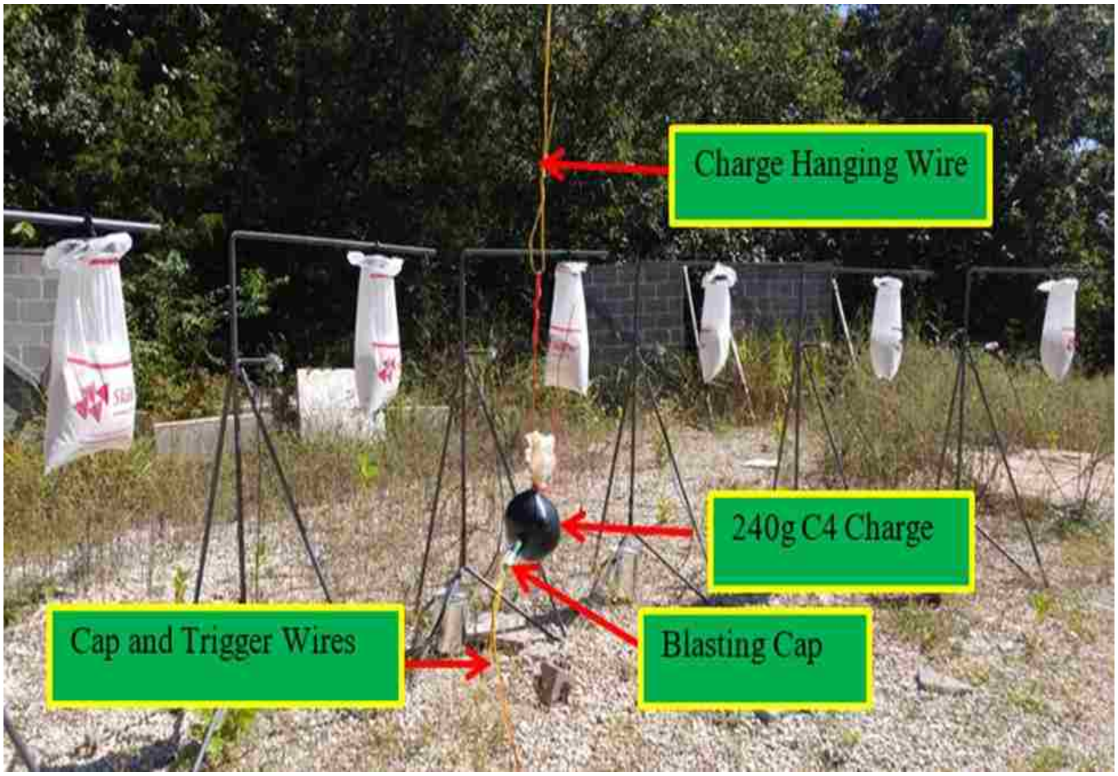
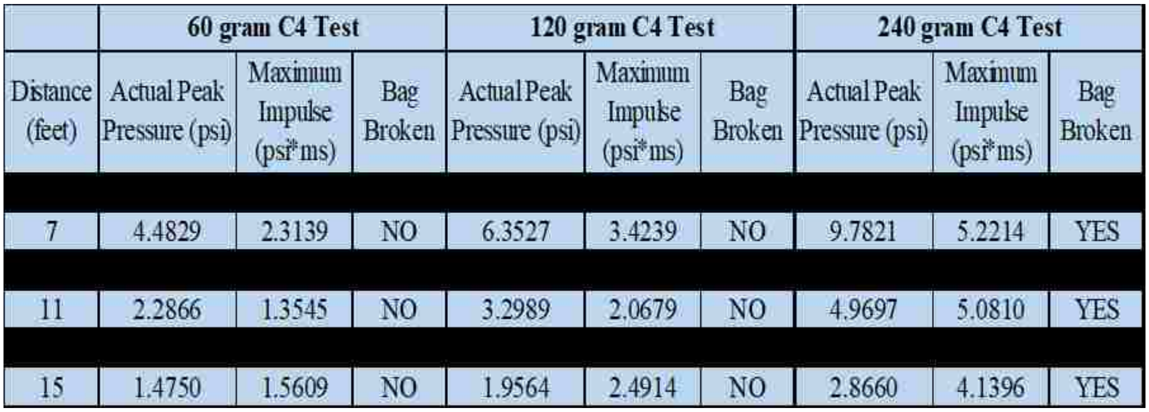


Figure 3.3: 240g Charge Hung with Blasting Cap and Trigger Wire

3.2.2. Open Air Testing Results. The results of the testing followed the anticipated trends. As expected, with an increase in charge weight, a resulting increase in peak pressure and impulse was observed at each distance. At 5 feet, the 240g C4 charge produced a peak pressure of 18.55 psi and an impulse of 7.09 psi*ms, whereas the 120g C4 charge resulted in a peak pressure of 11.66 psi and an impulse of 4.89 psi*ms, and the 60 g C4 charge resulted in a peak pressure of 8.73 psi and an impulse of 3.30 psi*ms.

Furthermore, as distance was increased from sensor position one, the pressures and impulses decreased as anticipated. For the 60g C4 test, the peak pressure decreased from 8.73 psi to 1.48, and impulse decreased from 3.30 psi*ms to 1.56 psi*ms. The 120g C4 test saw pressure decrease from 11.67 psi to 1.96, and the impulse decrease from 4.89 psi*ms to 2.49 psi*ms as distance increased from 5 to 15 feet. The pressure decreased from 18.55 psi to 2.87 psi, and the impulse decreased from 7.09 psi*ms to 4.14 psi*ms for the 240g C4 tests as the sensor distances to the charge increased from 5 to 15 feet. The key data from the open-air testing can be found in Table 3.1.

Table 3.1: Max Pressure, Impulse, and Bag Rupture Comparison



	60 gram C4 Test			120 gram C4 Test			240 gram C4 Test		
Distance (feet)	Actual Peak Pressure (psi)	Maximum Impulse (psi*ms)	Bag Broken	Actual Peak Pressure (psi)	Maximum Impulse (psi*ms)	Bag Broken	Actual Peak Pressure (psi)	Maximum Impulse (psi*ms)	Bag Broken
7	4.4829	2.3139	NO	6.3527	3.4239	NO	9.7821	5.2214	YES
11	2.2866	1.3545	NO	3.2989	2.0679	NO	4.9697	5.0810	YES
15	1.4750	1.5609	NO	1.9564	2.4914	NO	2.8660	4.1396	YES

Graphical representations of the pressure sensor waveforms from the 60-gram, 120-gram, and 240-gram C4 test shots can be viewed in Appendix B. The positive phase duration was calculated using Formula 1. Maximum impulse was computed using Formula 3. The bag breakage results, with respect to distance, peak pressure, and maximum impulse for the 60, 120, and 240-gram charge weights are shown in Table 3.1.

3.2.3. Open Air Testing Analysis. Only the position #1 (5 foot) bag broke during the 60g shot (Table 3.1). Each of the other bags for the 60g test remained unbroken. However, the 120g and 240g tests had bags that ruptured at pressures lower than some of those unbroken in the 60g test (Table 3.1). The bags that ruptured at lower pressures in the 120g and 240g tests than the 60g test experienced higher impulse values. This indicates the importance of impulse over pressure on the bag operation.

The 120g test had bags break at the #1 and #3 positions (5 and 9 feet), while the bag at position #2 (7 feet) with higher pressure and impulse than that of the bag at 9 feet remained unbroken. The 240g test demonstrates the pressure inconsistency between the bags at positions #5 and #6 (13 and 15 feet) as seen in Table 3.1. The bag at 15 feet ruptured with a peak pressure and max impulse that were lower than the pressure and impulse observed at 13 feet. However, the bag at 13 feet was unbroken. There are many factors that may have contributed to these inconsistencies. However, when the combination Peak Pressure versus Impulse (P-I) diagram was assessed; trends began to emerge, see Figure 3.4.

In analysis of the pressure-impulse versus damage diagram, there are no bags that broke near the reported 4.0 kPa (0.58 psi) threshold for claimed operation of the bags, as indicated by the red vertical line in Figure 3.4. The lowest pressure of a bag that did

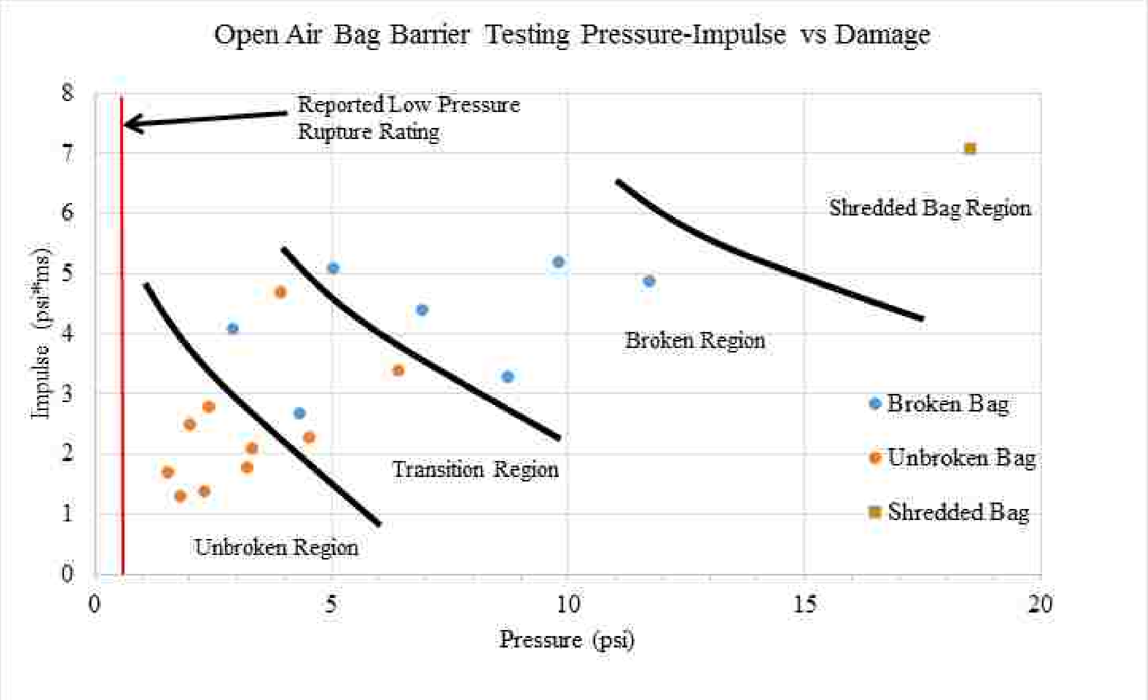


Figure 3.4: Open Air Bag Barrier Testing Pressure-Impulse versus Bag Damage

break was 2.87 psi, or 19.79 kPa. However, this lowest pressure ruptured bag also had a significantly higher contributing impulse value. The data also shows four distinct regions of bag damage; an unbroken region where no bags break because the combination of pressure and impulse are too low, a transition region in which some bags break and others do not, a broken bag region where all the bags are at least splitting open, and a bag shredding region where the bags are likely to be completely shredded and dust released.

This overall region of testing displayed in the open-air pressure-impulse diagram clearly defines the dynamic damage response region of the barrier bags. It also highlights the threshold for bag damage in this combination pressure and impulse range. This dynamic response region is typically the most difficult region to define. However, the open air-testing does not clearly define the impulse sensitive asymptotic region as well as previously anticipated. Additional testing focused on a relatively high pressure (15 to 20 psi) and relatively low impulse (1 to 3 psi*ms) would be required to help define this region better.

In all cases of ruptured bags however, the contained dust was not dispersed but merely dropped straight down from the bag, if it came out of the ruptured bag at all, as seen in Figures 3.5 and 3.6. The orientations of the bags with respect to the blast wave, or the air pressure within the bags themselves, are two of the many possible factors that may have affected the bag breakage. The typical result of those bags that did rupture during the testing ranged from just a small tear to completely shredded at the closest distances, as seen in Figures 3.6 and 3.7. Additional pictures of bag damage caused during the open-air testing can be viewed in Appendix C.

It is apparent that pressure alone is capable of rupturing the bags, if high enough. However, pressure alone is not the driving force for the dispersal of the stone dust contained within the barrier bags, as evidenced by a complete lack of dust dispersal in all open-air tests. In the open-air tests, those bags that did rupture either dropped their load straight to the ground, or the tearing of the bag was not sufficient to release the dust at all. It would appear then that it takes a combination of sufficient pressure to rupture the bag enough to release the dust, along with an adequate impulse to disperse the dust once it is released. This hypothesis was tested further with the testing performed in the shock tunnel.

As discussed in Section 2.5 of this thesis, early bag barrier testing and development was performed at the Kloppersbos testing facility in RSA. This testing facility utilized a 2.5-meter diameter by 200-meter-long, methane gas explosion driven,

Figure 3.5: Picture Showing Typical Pattern of Dropped Stone Dust

Figure 3.6: Picture Showing Split in Bag Typical at Greater Distances

Figure 3.7: Picture Showing the Shredding of Bags Typical at Lesser Distances

shock tunnel for their barrier bag testing. However, those researchers did not perform testing of the bags in open air. By only testing in a shock tunnel, the separate characteristics of the pressure and impulse effects cannot be distinguished, and the understanding of the bag barrier operation is incomplete. To illustrate this difference between the pressure and impulse effects on the barrier bags, the open-air testing was followed by additional testing in a shock tunnel located at the Missouri University of Science and Technology Experimental Mine Site. Though the shock tunnel used was of a different configuration than that of the South African facility, the pressure and impulse funneling effect experienced was sufficient to exhibit the distinction between the effects of each on the barrier bags.

3.3. SHOCK TUNNEL TESTS

This experiment consisted of four test shots performed in a fabricated steel shock tunnel. The overall dimensions for the tunnel are approximately 65 feet long, by 6 to 8 feet tall, by 3 to 6 feet wide. The height and width of the tunnel vary along the length using smooth transitions between the different sizes as seen in Figure 3.8 and Figure 3.9. The charges and stone dust bags were hung from hooks welded along the inside length of the tunnel roof at 2-foot intervals. All tests were performed with explosive charge sizes of 40 grams of C4 to obtain a similar pressure range as in the open-air testing. The distance between the charge and the end of the tunnel nearest the charge was increased for each test. This effectively decreased the distance between the charge, and the pressure transducers and barrier bags which remained in the same locations for all tests. To prevent damage to the pressure transducers from rupturing bags, falling stone dust, and flying debris, testing performed on actual barrier bags was performed separately, but under the same stringent setup regiment to acquire the pressure data. The equipment and supplies required to perform the shock tunnel testing are listed in Appendix D.

Figure 3.8: Fabricated Steel Shock Tunnel Used for Barrier Bag Testing

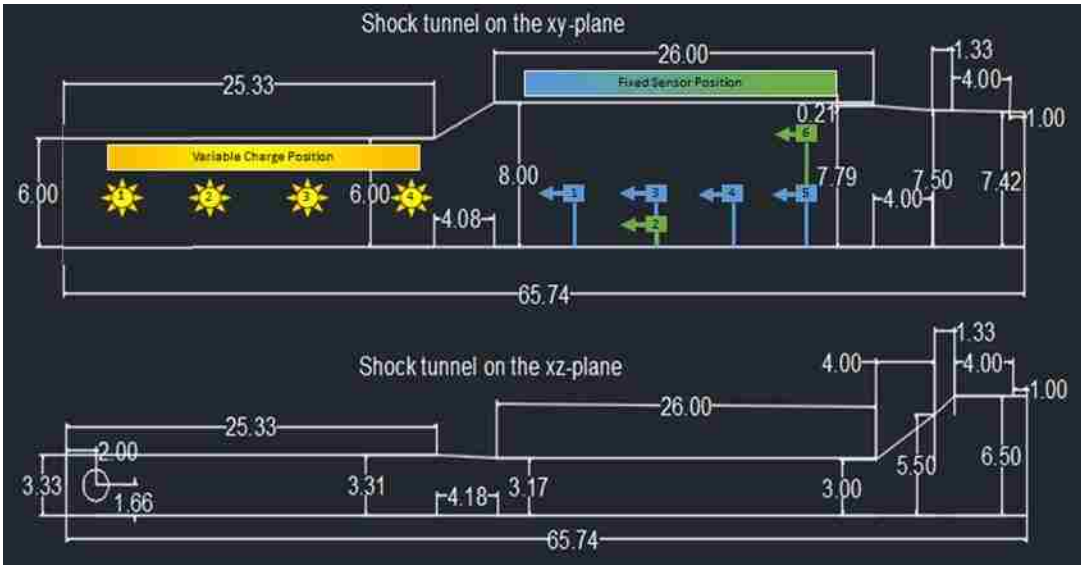


Figure 3.9: Dimensional Drawing of Fabricated Steel Shock Tunnel[47]

3.3.1. Shock Tunnel Pressure Testing Method. The goal was to record the pressure versus time data of several tests, and analyze the recorded data to determine the peak pressure and calculate the maximum impulse attained. Additionally, the resulting damage, or lack of damage, to the barrier bags was recorded. This allowed direct correlation between the peak pressure, maximum impulse, and the damage to the bag barrier system.

The shock tunnel has chain links welded to the inside of the roof at 2-foot intervals from the small opening end to the middle of its length. The charge hanging wire was attached to the chain link 4 feet from the small end of the tunnel with sufficient length to be able to hang the charge at the midpoint of the tunnel later. The six pencil probe pressure transducers were mounted in specially made holders attached to weighted camera tripods. A measurement of 35 feet was made from the small end of the tunnel, and the #1 sensor was fixed into position at the cross-sectional midpoint of the tunnel. Two sensors were located at the 43-foot distance from the small end of the tunnel, the #2 sensor at the midpoint horizontally and 1 foot from the floor, the #3 sensor at the cross-sectional midpoint of the tunnel. At 51 feet from the small end of the tunnel, pressure transducer #4 was installed and fixed at the cross-sectional midpoint of the tunnel. At 57 feet from the small end of the tunnel the #5 pressure transducer was fixed it at the cross-sectional midpoint of the tunnel; while the #6 sensor was installed at the midpoint of the tunnel horizontally and 6.5 feet from the floor. Pressure sensor distances from the given charge are detailed in Table 3.2.

Table 3.2: Pressure Transducer to Charge Distance in Tunnel

[redacted]

Upon completion of the pressure transducer setup, four of the six pressure transducers were collinear at the cross-sectional midpoint of the tunnel. The remaining two transducers were placed to monitor for pressure abnormalities near the floor and roof of the test tunnel. A standard blasting cap was prepared with a trigger wire pigtail taped over the end so the pigtail wire would be broken upon blasting cap detonation, signaling the time of detonation to the DAS. The previously prepared 40-gram C4 charge was hung from the charge hanging wire at the cross-sectional midpoint of the tunnel at the specified distances (4, 12, 16, and 20 feet from the small end of tunnel) for each test.

3.3.2. Shock Tunnel Barrier Bag Testing Procedure. Four barrier bags were tested separately using 40-gram C4 charges placed at 4, 12, 16, and 20 feet from the small end of the tunnel, the same setup as the pressure testing. The barrier bags were hung at the pressure transducer #4 location for all four of these tests. This location was 51 feet from the small end of the tunnel, and was chosen because the range of pressures and impulses developed at this distance were within the range of the open-air testing.

In all other facets, the shock tunnel bag testing was performed in the same manner as the shock tunnel pressure tests. The resulting effects of the explosion tests on the barrier bags was recorded, as well as the degree of dispersion of the enclosed stone dust. Dust dispersion classifications were based on visual observations and divided into three classes; no stone dust release, stone dust release but no dispersal of dust directed away from the explosive charge, and stone dust release with significant dispersal directed away from the charge. Steps required to prepare for additional tests were similar except that a new charge and blasting cap were prepared and hung at the different distances required for each respective test (4, 12, 16, and 20 feet from the small end of tunnel). Additionally, a new pre-filled barrier bag was hung at the same location for each test, and the stone dust dispersed from the previous test was swept out of the tunnel end.

3.3.3. Shock Tunnel Testing Results. The results of the shock tunnel testing are important to help differentiate the pressure versus impulse effects of a mine explosion on the operation of the bag barrier system components. The understanding of this difference and the effect of the explosion impulse on the bag barrier system is imperative. Appendix

E contains the pressure and impulse data from the shock tunnel testing. Table 3.3 compares the resulting maximum pressure and impulse values at the barrier bag location for each charge distance within the tunnel, with the observational results of the barrier bags after each test. The charge distance to the barrier bag ranged from 31 to 47 feet. The maximum pressure at the barrier bag location ranged from approximately 2.4 to 3.1 psi. The maximum positive impulse ranged from approximately 8.1 to 11.0 psi*ms at these distances. In all cases the barrier bags were ruptured with the contained dust having been dropped and dispersed to varying degrees.

Table 3.3: Barrier Bag Damage versus Distance, Pressure, and Impulse

[redacted]

3.3.4. Shock Tunnel Testing Analysis. As the charge distance into the tunnel increased, the distance between the charge and the pressure transducer locations decreased. This is due to the fixed location of the sensors within the tunnel. The general trend for pressures and impulse was as expected, with lowest values occurring at longest charge to transducer distances, and largest values occurring at shortest charge to transducer distances; with the exception of the 12-foot test. The 12-foot test demonstrates how the incident and reflected shock waves can interact constructively at periodic distances. The maximum pressures obtained during tunnel testing ranged from 2.0 to 5.2 psi, at charge to transducer distances from 53 to 15 feet. The maximum positive impulse values ranged from 6.5 to 15.8 psi*ms at the same distances. Some slight variations to this trend in pressure can be noticed in the data for sensors 2 and 6. This is due to their location away from the collinear position of the other sensors and toward the floor and roof, and due to the reflection of the shock wave. The lack of major variations in arrival time between the collinear sensors and the ones mounted near the floor and roof indicate that the shock wave is planar when it reaches the sensors.

The barrier bags were tested at sensor location 4. This yielded a charge to barrier bag distance that ranged between 31 and 47 feet for the various tests. The pressures obtained at sensor location 4 in the previous testing ranged from 2.3 to 3.1 psi; while the impulse values ranged from 8.1 to 11.0 psi*ms for those same distances to the sensor 4 position. In all tests, the barrier bags ruptured and dispersed the contained dust to various degrees, unlike the open-air testing. The shorter charge to barrier bag distances, with resulting higher pressure and impulse values, consistently and clearly displayed a greater degree of bag tearing and dust dispersal than that of the greater charge to bag distances, as seen in Figure 3.10. Additional figures of the shock tunnel testing are contained in Appendix C (C2.1 – C2.3).

By combining the shock tunnel testing data with the open-air testing data on the pressure impulse diagram, Figure 3.11, a new region is uncovered. This new region shows an area of dust dispersal at low pressure but relatively high impulse. This region helps to define the pressure sensitive asymptotic region of the bag specific pressure-impulse graph. This indicates the importance of impulse on the release and dispersal of dust at low pressures. Also, it appears that consistent dust dispersal begins to occur around 8psi*ms, as the open-air test bag that shredded had a significantly higher pressure, but an impulse value slightly lower than 8psi*ms, and no dust dispersal was noted.

Figure 3.10: Picture Showing Bag Shredding and Dust Dispersal Typical of Shock Tunnel Testing

Also, all of the bags tested above 8psi*ms ruptured and dispersed dust. Unfortunately, the open air and shock tunnel testing left a region undefined in the pressure-impulse diagram, the impulse sensitive asymptotic region. To further define that region, some additional testing would be required to be designed and performed to focus on relatively high pressures in a much lower impulse region.

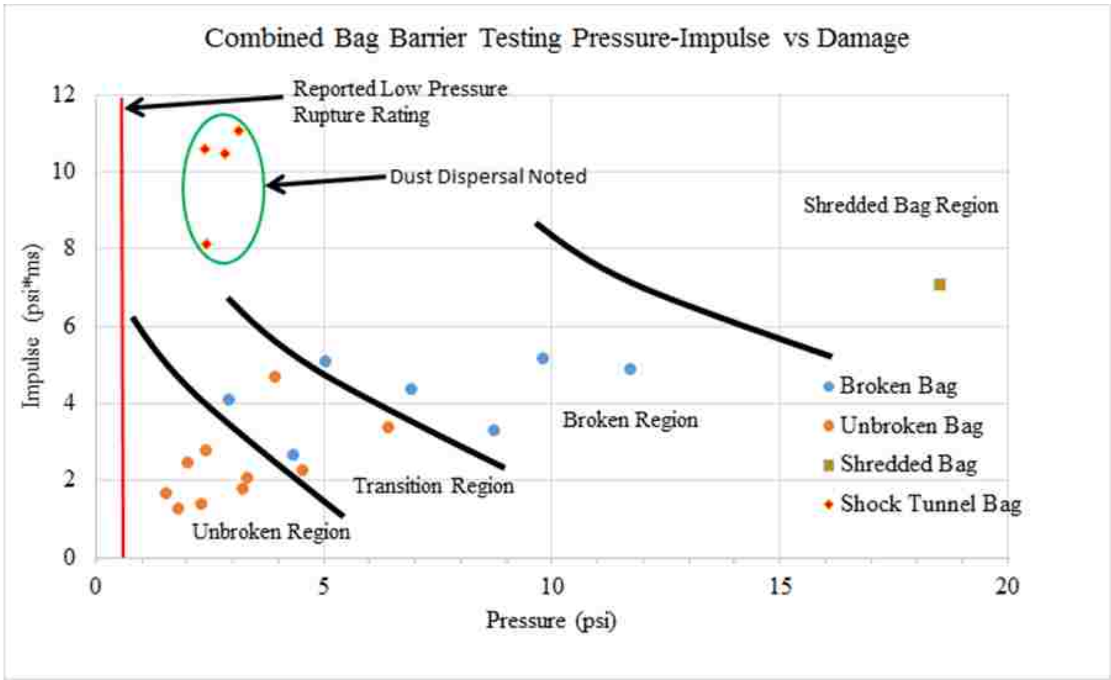


Figure 3.11: Combined Bag Barrier Testing Pressure-Impulse versus Damage

3.4. SUMMARY

In performing testing of the barrier bags in open air versus a shock tunnel, a comparison can be made. This comparison depicts the impulse effects of an explosion on the barrier bags' rupture and dust dispersal. In the open arena testing, a larger range of pressures, and higher overall pressure, were obtained (1.4 to 18.5 psi) versus that of the shock tunnel testing (2.3 to 3.1 psi). Conversely, the shock tunnel testing developed a larger overall impulse (8.1 to 11.1 psi*ms) compared to the open arena testing (1.6 to 7.1 psi*ms) but in that narrower range of pressure. By comparing the barrier bag rupture characteristics under these two diverse conditions, and resulting pressure and impulse parameters, it can clearly be seen that pressure alone cannot consistently rupture the bags unless it is veryrelatively high, and especially not to the extent that is required to dump and disperse the entire amount of contained stone dust. Furthermore, in zero open arena tests was stone dust dispersal noted.

Moreover, by comparing the open arena testing to the tunnel testing, the importance of the shock impulse on the shredding of the bags, and the dropping and dispersal of the contained stone dust, became evident. The open arena test that resulted in the highest pressure and impulse values (18.5 psi and 7.0 psi*ms), displayed shredding of the bag and dropping of the contained stone dust, but no dispersal of the dust was noted. In effect, the bag shredded at the air gap and dropped the entire load of stone dust in one pile. Conversely, the tunnel test resulting in the lowest pressure and impulse values (2.3 psi and 8.1 psi*ms) displayed similar bag shredding, but with reduced dust drop and increased dust dispersal directed away from the location of the charge. In all tunnel tests the barrier bags were shredded and the dust was partially dispersed. Only a handful of open arena tests at the highest pressures displayed shredding of the bag, while none of these displayed any dispersal of the stone dust.

4. IMPLEMENTATION OF BAG TYPE PASSIVE EXPLOSION BARRIERS IN U.S COAL MINES

4.1. MINE SITE TRIAL INSTALLATION OVERVIEW

In order to determine if the bag barrier system could be implemented into American underground coal mines, arrangements were made with two cooperating underground longwall coal mines in the Eastern United States to install scaled length barrier arrangements in development entries within their mines. The barriers were to be left in place for 4 to 5 weeks, and then were inspected, sampled, and removed upon return to the mine. This length of time would allow both mines to advance the development of their respective entry through the barrier. Additionally, this would allow ample time for various development crews and other miners to work around and experience the bag barriers in place.

Upon arrival to install the bag barriers, miners were surveyed on their knowledge of coal mine disasters, their causes, methods of coal dust explosion prevention, and their feelings of safety in their workplace. Upon return to inspect, sample, and remove the bag barriers the miners at each mine were again surveyed. This survey asked about their concerns and experiences with working around the bag barriers, their understanding of the barriers, and the bag barriers’ effect on their perceived safety. Additionally, miners and engineering staff were asked to give any input or suggestions for the improvement, adaptation, or implementation of the bag barriers into their mines. The results of these surveys and the summations of the mine site trials follow.

4.2. BAG BARRIER INSTALLATIONS

Scaled length bag barriers were installed in 2 operating coal mines. They were both installed in the intake air entries ahead of major development. One was installed in the track entry, while the other was in the power and piping entry. The barriers were left in place for a month to allow time for the progression of mining development through the barrier areas. The following sections (4.2.1. and 4.2.2.) contain the details of installation.

4.2.1. Trial at Mine #1. To prepare for the trial bag barrier setup at #1 mine, and to simulate how barrier bags arrive at mines internationally, the barrier bags were pre-filled with the required amount of stone dust, loaded into boxes, and shipped to the mine in advance. Some minor shipping damage to one corner of the container was visible upon arrival, and some of the bag hooks pierced the cardboard dividers and punctured the adjacent bags as seen in Figure 4.1. Twenty-two percent of the total shipment of barrier bags were damaged by transport or hook protrusion. This was due to inadequate shipping materials being used and could be easily addressed and corrected.

Figure 4.1: Damage to Bags from Packing and Shipping to Mine

Roof mesh was absent in most locations throughout mine #1, and the bolt spacing was wider than conducive for the recommended bag spacing 0.4 to 1 meter (1.3 to 3.3 ft) as outlined earlier in Figure 2.2. To assist with a mounting alternative, various hooks were sourced and tested, of which three met the criteria for the installation atmosphere, cost, and load capacity. The hook options (Figure 4.2) were shipped to the #1 Mine site along with the prefilled barrier bags. The #3 Hook was quickly eliminated as a viable alternative because it did not work with the roof straps, and the top hook was bent too tightly to easily fit through the loop in the roof bolt plates. The #2 Hook worked well with the roof bolt plates, but not with the roof straps. The #1 Hook worked well with roof bolt plates and roof strap, but it was seen to have directionality; meaning should the bag or hook be pushed in the opposite direction to which it was installed, the #1 Hook could slide off and become dislodged from the bolt plate or roof strap. This condition is less than ideal for the bag barrier to function properly, as the bags could be dislodged from the roof straps during an explosion if installed incorrectly on the outby side of the support.

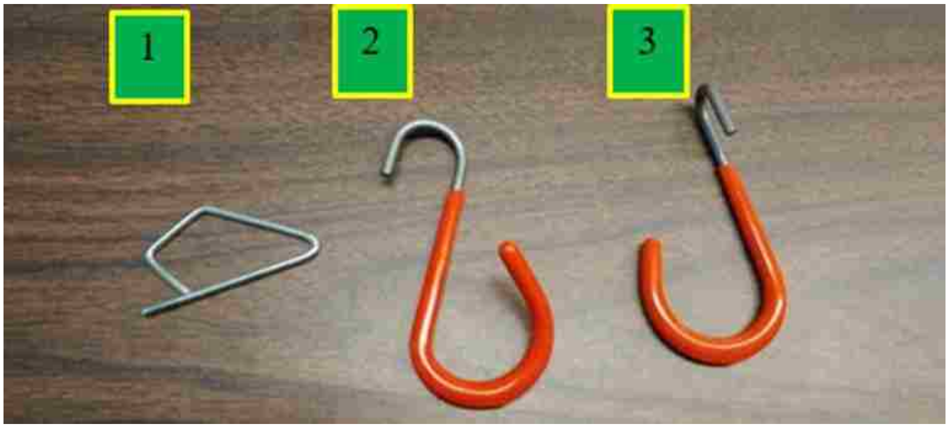


Figure 4.2: Hook Types Examined for Mounting Alternatives

Since the roof bolt plate spacing was wider than the recommended barrier bag spacing, another method of supporting the barrier bags was needed. The challenge was to develop this method of support using supplies readily available within the mine. One such method employed, used an extra length of cable attached to the outermost bolt plate loop, threaded through each roof bolt plate loop in that row, and drawn tight at the opposite, outermost bolt plate loop using a small turnbuckle or bolt, nut, and washers (Figure 4.3). The barrier bags were then hung directly from the section of cable. Another method employed for hanging the barrier bags with recommended intra-row spacing involved the use of pre-made cables with hooks stretched between bolt plates using available hardware. Again, the barrier bags were hung directly from these cables (Figure 4.4). The final method employed to hang the barrier bags with recommended intra-row spacing involved using available rubber coated cable hangers to span the distance between bolt plates. The barrier bags were then hung directly from the cable hangers (Figure 4.5).

Figure 4.3: Bolt Plate/Cable Support Method

Figure 4.4: Cable and Hook Support Method

Figure 4.5: Rubber Coated Cable Hanger Support Method

These three alternative support methods were implemented to show some of the possible means of hanging the bags with recommended spacing, should roof bolt plate spacing be too wide, and/or without the use of roof mesh. The majority of bags were hung directly from the bolt plates with the use of the #2 Hooks. The #2 Hooks were necessary because the bag closure/hook does not fit through the bolt plate loop or on the roof strap mounting. The concern with using the #2 Hooks was the additional length that the barrier bags hang down; approximately 4 inches versus hanging the barrier bags directly. Once the installation was complete, a battery-operated scoop car was positioned to determine the amount of clearance between it and the hanging bag barrier (Figure 4.6). 9-12 inches of clearance were observed, depending on the roof/floor conditions. Employees assisting with the installation can be seen as a frame of reference.

Figure 4.6: Scoop Car versus Bag Barrier Clearance

A Bag Barrier Supplies Calculator spreadsheet, based on UK standards and included in Appendix F, was created and used to determine the amount of stone dust and the number of bags and hooks required for different types of barrier installations. The maximum amount of stone dust and number of bags/hooks required would be 6,480 kg

(14,286 pounds) of stone dust and 1,080 bags and hooks per entry. For a three entry headgate and tailgate supporting a typical longwall section, that would equate to 38,880 kg (85,716 pounds) of stone dust and 6,480 bags and hooks. The recommended locations to install these barriers in this section are the yellow highlighted areas in Figure 4.7. To install the barriers in this mine as depicted would require 64,800kg (142,860 pounds) of stone dust and 10,800 bags and hooks. Note that exact barrier lengths and positioning depend on the barrier configuration used; Figure 4.7 depicts the use of distributed barriers. The small red boxes are the recommended range in which the barrier should begin (approximately 200–400 feet from the longwall face or last open continuous miner crosscut). The trial barrier installation was completed in the Longwall #2 track entry, between breaks 19 and 21, approximately 800 feet from the face. The trial barrier installation location is the light green section (inside the red circle) in Figure 4.7.

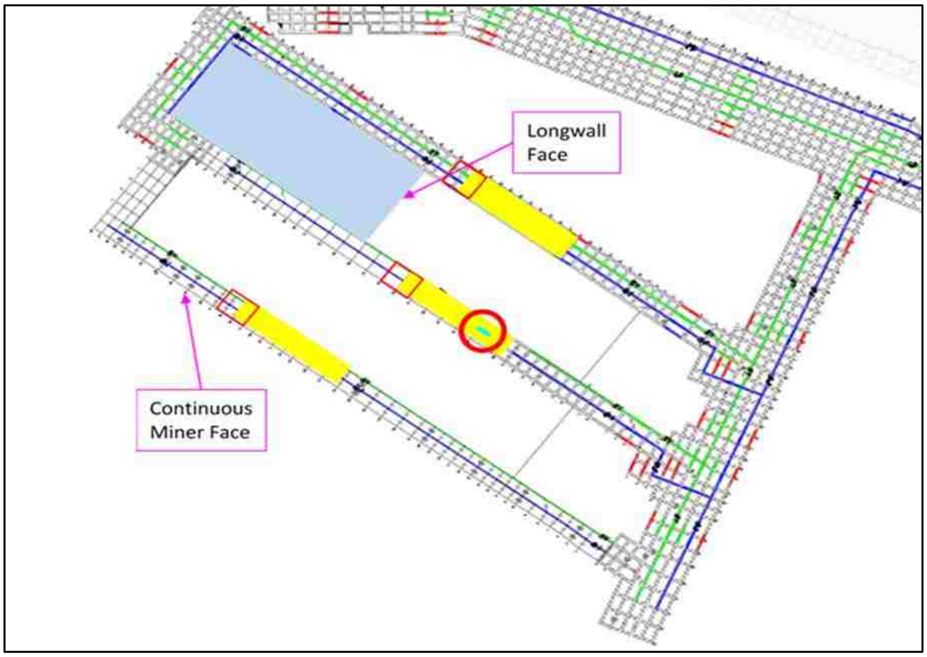


Figure 4.7: Barrier Installation Location Mine #1

4.2.2. Trial at Mine #2. No shipping damage was noted to the shipping cartons upon inspection at mine #2. However, similar hook puncture damage to the barrier bags occurred. Seventeen percent 17% of the bags, ones in the lower levels especially, suffered damage from this issue. In addition, several barrier bag closure and hook assemblies were bent and deformed by the weight of the layers of prefilled bags above. The #2 Mine used roof mesh in most entries on development, making barrier installation very straightforward. The only complication noted for installation of the barrier bags was the height of the mine roof (approximately 9 feet). A ladder was needed to hang the barrier bags (Figure 4.8) which increases the amount of time required for installation, causing increased costs of installation. The original bag closure and hook assembly was easy to hang directly on the roof mesh (Figure 4.9), although the mesh had to be pulled down

Figure 4.8: Miner Hanging Bag from 8 Foot Ladder

away from the roof rock in some places to have enough clearance for the hook assembly to fit between the mesh and the rock. This raised concerns for potential damage to the hook over time as the roof mesh holds more load and fractured roof rock due to the spalling or flaking off of the roof rock layers. The Australian consultants reported that the added load of fractured roof rock is a non-issue in other countries utilizing the bag barriers. Due to the roof height, interference of the barrier bags with men or equipment was not expected to be an issue. There was approximately 1 foot of clearance over a 6 feet tall miner and at least 2 feet of clearance over a scoop car (Figure 4.10).

Figure 4.9: Barrier Bag Hung from Roof Mesh

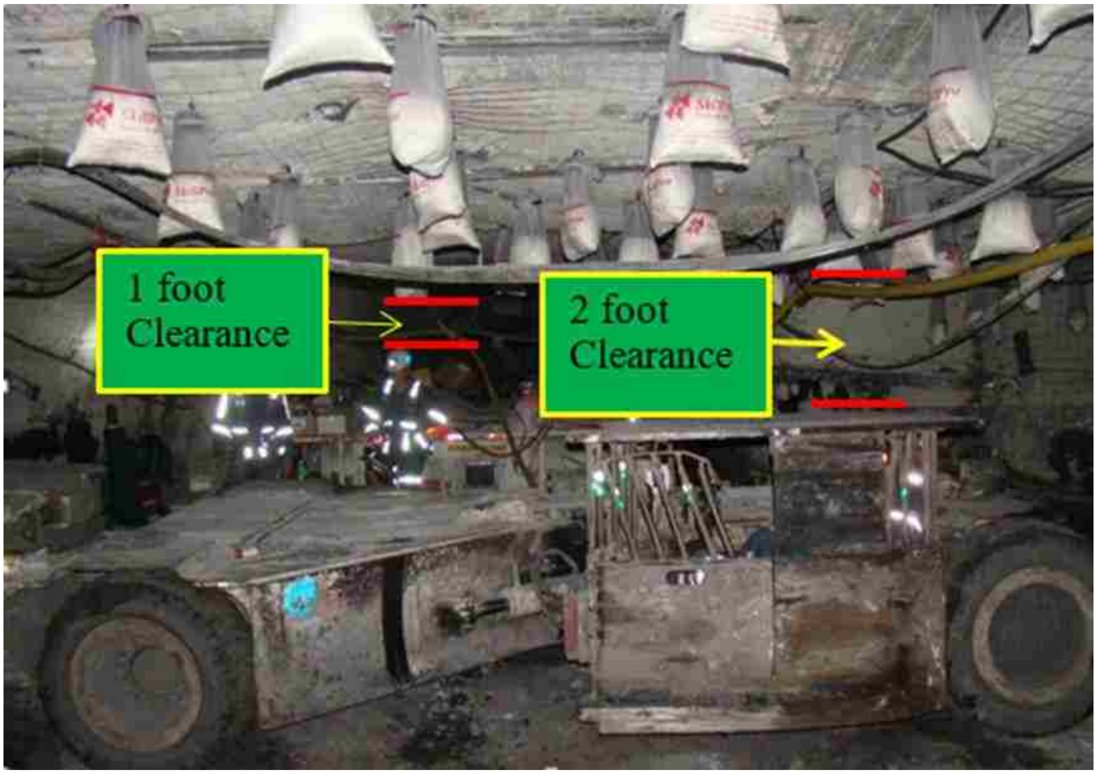


Figure 4.10: Scoop Car and Miner Clearance with Barrier Bags

The Bag Barrier Calculator spreadsheet was again used to determine the amount of stone dust and the number of bags and hooks required for different types of barrier installations in mine #2. The completed sheet can be viewed in Appendix F. The maximum amount of stone dust and number of bags and hooks required would be 7,575 kg (16,700 pounds) of stone dust distributed with 1,260 bags and hooks per entry. For a typical 3 entry headgate/tailgate combination would require 45,450 kg (100,200 pounds) of stone dust and 7,560 bags and hooks. The recommended locations to install these barriers are the yellow highlighted areas in Figure 4.11. To install the barriers as depicted in this mine, to protect the longwall and the continuous miner development, would require 90,900 kg (200,400 pounds) of stone dust and 15,120 bags and hooks. Note that exact barrier lengths depend on the barrier configuration used; Figure 4.11 depicts each barrier as a distributed barrier. The green boxes are the recommended range in which the barrier should begin (approximately 200-400 feet from the longwall face or last open continuous miner crosscut). Note that the barrier near the continuous miner face must split at the gate-road/sub-main junction to meet minimum barrier length requirements, adding to the number of bags required. The trial barrier installation location is the light green section (inside the red circle) in Figure 4.11. Note that this map had not been updated to show recent progress; the top two panels had been fully mined, and the bottom two gate-roads had been fully developed.

The purpose of installing partial bag barriers in active mines was to determine any potential issues with working around the system. The partial barriers were completed, and re-inspected upon return after 4 to 5 weeks, to examine the condition of the barriers and gain feedback from the miners. Additionally, management and labor forces were surveyed prior to installing the bag barriers and upon returning to the mine sites to inspect, sample, and remove the barriers regarding their interactions with, and opinions of, the bag barriers.

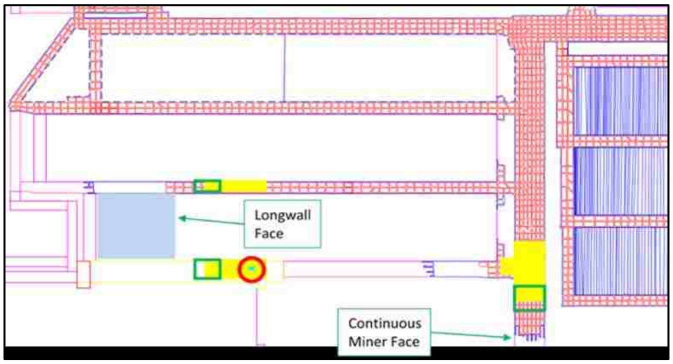


Figure 4.11: Trial Barrier Installation Location Mine #2

4.3. SURVEY RESULTS

Both pre- and post- installation surveys were conducted with the members of the workforce who assisted with the partial barrier's installation. Additionally, a follow up survey was conducted with those who worked around the barriers during the intermission between installation and re-inspection. Each of the surveys were given to employees from a variety of job classifications, including engineers, foremen, electricians, shuttle car operators, and safety foremen. These surveys gave vital feedback on various aspects of barrier installation and the effects they had on the performing of various job duties in the mine.

4.3.1. Preliminary Survey. The preliminary survey contained six questions designed to determine the survey participants' familiarity with methane and coal dust explosion hazards related to coal mining, as well as their familiarity with the bag barrier system itself (Table 4.1). Seven employees were available to assist with the installations at both mines. Of these, all were familiar with recent mine disasters caused by methane and coal dust explosions and the potential for such explosions in coal mines. Five of the seven employees believed current explosion prevention standards are inadequate, though two of these commented that the prevention methods used will never seem sufficient as long as ignitions still occur in U.S. mines. All survey participants believed that more should be done to prevent and mitigate coal dust explosions, however most also commented that prevention methods could always be made better. Only two of these miners were familiar with the bag barrier system, although both had only briefly heard of it and did not know any specific details. Note that one employee declined to comment on question 5.

Table 4.1: Preliminary Survey Results

[redacted]

4.3.2. Post-Installation Survey. The post-installation survey consisted of ten questions designed to gain feedback from those who assisted with the trial barrier installation. Table 4.2 contains the results of the survey. Questions 3, 5, 7, and 9 asked for further explanation of positive responses to the prior question, and question 10 asked for additional comments. These questions are withheld from Table 4.2 but are discussed further below.

All the miners felt the barrier was easy to install. Only one reported any installation difficulties; this employee worked in the mine that did not normally use roof mesh and reported issue with developing a method for hanging the bags at the appropriate spacing, as previously discussed. Many had suggestions for system improvement, and the same three concepts were heard from several different employees: (1) adding a wide circle around the hook assembly to protect the bag from damage due to falling roof rock,

(2) a redesign of the hook to decrease hanging length, and (3) a redesign of the hook to be stronger than the current plastic design.

Table 4.2: Post-Installation Survey Results

One of the miners assisting with the installation suggested a modified hook and closure design, which utilized a small hole with a free moving steel hook instead of a fixed plastic design (Figure 4.12). This allows for easy hanging of the bags from roof bolt plates, roof mesh, or cables without the additional length inherent to using the additional #2 Hooks. Also, the wire hook can lie flat, eliminating the transport damage issues that were observed. However, the design would not work on roof straps and would also need additional testing to verify that the bags would still operate properly.

Four employees foresaw potential issues with the system. The three issues stated were: (1) damage to the bags during regular moving of power stations and cables, and belt conveyor systems, (2) additional labor required for bag installation as mining progresses, and (3) damage to the bags from rock falls. Concerns mentioned by engineering staff during discussions were: the flammability of the bags themselves, MSHA approval for installing the bags in a U.S. coal mine, the need for dusting or maintaining dust on the outside of the bags, and the impedance to ventilation created by the installation of the barrier bags. A prominent concern was the added costs of the bags and hooks, along with the additional labor required to install and maintain the bag barriers. Furthermore, MSHA fines for non-compliance were a concern should the system become mandated, regulated, and inspected in America.

Figure 4.12: Modified Closure/Hook Design Suggestion

4.3.3. Follow-Up Survey. Upon return to the mine sites after 5 weeks to inspect the barriers and sample the rock dust, mine employees on that shift who worked in the vicinity of the barrier systems were surveyed about any interactions they had with the barriers. Their feedback was collected and recorded. Table 4.3 shows the results of the surveys given to mine management, while Table 4.4 shows the results of the survey taken by the miners.

Regarding the management surveys, question 1 was directed more at mine #1 since a directional hook/clip was used to hang many of the bags from the roof straps. It was unclear if this directionality of installation would allow the clips to become dislodged if they were bumped in the direction opposite of installation. From the survey results, it became apparent that this was not a large concern. The survey response options related to the number of bags, while the percentage value was the percentage of respondents who gave that number.

The disparity between the number of bags broken at the different mines during the trials in question 2 (3 or less versus 50 or more) was due to the differences in the mines and trial locations within the mine. Mine #1 had a lower roof, and the barrier was installed in the track entry. Therefore, when the track was being laid through the area and power cables were being moved, the miners decided to remove the bags, set them aside, and reinstall them afterwards, rather than work around them. In doing so, the bags were damaged by rough handling and being set down on jagged bits of rock and coal alongside the ribs that poked holes in the bags. These holes would turn into tears upon being picked up and re-hung. Upon return to the mine and performing barrier inspection, only 35 barrier bags of the original 114 that were hung survived being taken down and rehung. It was assumed that a small fraction of these were due to vandalism and pranks as well. This was confirmed by answers to question 3 concerning how the bags were broken. It was reported that some bags were cut by knives, meaning that the miners were pranking their co-workers by getting them to stand under a bag, then “dusting” them by cutting the bag open and letting the dust fall onto them. However, the majority of bag damage was reported to have been caused by moving the bags, laying track, and unloading supplies. It was also reported that zero accidents or injuries were caused by the bag barriers and the workers' interactions with them.

Table 4.3: Mine Site Management Survey

[redacted]

Table 4.4: Combined Mine Site Labor Survey

[redacted]

Regarding the labor surveys, 80% of workers in the vicinity of the barrier trials had some interaction with the barriers; while 93.3% of miners understood the purpose of the barriers. The same 6.7% that did not understand the bag barrier's purpose in question 2 did not respond to question 3. The purpose of the bag barrier was explained to 20% of the workers who were unaware of its intended purpose, while the remainder learned of the bag barriers’ purpose from their co-workers. The collection of problems experienced with the barrier systems, and reported in question 4, were that the bags were: easy to bust open or tear, hung too low, and were generally in the way. The main problem experienced and reported was torn or busted bags.

Some problems that miners could foresee with the bag barriers as mining progressed, and reported by question 5, were: advancing the bags as mining progresses due to broken bags, difficulty hauling prefilled bags through the mine and hanging them where required, the related costs, and locating them to avoid accidental destruction. Suggestions made for system improvement in question 6 were to use stronger bags that did not hang down so low, place them in the returns only, leave them stationary at high points in the mine, and to develop a “single unit” installation rather than hundreds of individual bags. However, many of these suggestions do not take into account the design principles of the bag barrier system. Stronger bags would not rupture at lower explosion pressures, smaller bags that did not hang so low would not contain adequate amounts of rock dust, explosions occur and travel down all entries not just the returns, and the logistics of trying to mount and hang a single unit that contained sufficient rock dust is impractical in the confines of an underground mine.

According to question 7, only 13.3% of the miners had considered intentionally breaking a bag to prank coworkers, or to get the bag out of their way. Forty-six and seven tenths percent (46.7%) of miners reported that having bag barrier systems in place would enhance their sense of workplace safety, 33.3% said that it wouldn’t, and 6.7% reported that it ‘may’ enhance their sense of workplace safety. The surveys were undertaken by a wide cross section of employees, including: scoop operators, roof bolters, laborers, shift and production foremen, safety officers, electricians, mechanics, and even an MSHA Inspector on site that day.

4.3.4. Analysis of Mine Surveys. The mine surveys provided valuable information regarding the implementation of the bag barrier system into operating mines in the United States. All the miners surveyed indicated their desire for additional safeguards against deadly coal dust explosions. The miners rated the bag barrier system an easy installation, and 86% felt safer with the barriers in place. Most importantly, zero injuries were incurred due to the bag barrier system being in place. These results indicate the miners are in favor of an additional layer of safety. If the miners want and approve of an added safety measure, such as the bag barrier system, they are more likely to help support, implement, and promote its proper use. This is an important consideration for a mine manager considering the implementation of such a safeguard.

4.4. BARRIER BAG MOISTURE INTRUSION STUDY

A major concern that was raised by mine site engineers and laborers during the trials was the barrier bags’ ability to prevent moisture contamination of the enclosed stone dust over time. To address this concern, a 12-month study on moisture contamination of the enclosed rock dust was performed at the Missouri S&T Experimental Mine. Additionally, barrier bags from each mine site trial installation were sampled and tested after 5 weeks in their respective mine settings. The results of each analysis follow.

4.4.1. Year-Long Study at Missouri S&T. The portion of the S&T Experimental Mine that was used for a long-term trial installation of the bag barrier system was of comparative width and height dimensions as the two operating mine site trials. This section had roof mesh installed, simplifying barrier bag installation. The distance required to construct a full-scale barrier was not available in the Missouri S&T Experimental Mine. So, a reduced length trial installation was performed, which maintained the recommended bag and row spacing but reduced the total number of rows. A total of 35 bags were hung (Figure 4.13). The roof height required a ladder to hang the bags. Several bags were broken during installation from being handled too roughly.

The scaled bag barrier installation at the Missouri S&T experimental mine was be left in place for 12 months; and the dust from 20% of the bags (labeled in Figure 4.13) was periodically tested for moisture content using ASTM specification C25-11; the full procedure can be referenced for more information on the ASTM website. In addition, the supply of dust used to fill the barrier bags was initially sampled and tested. To conclude the long-term trial, samples were taken from all 35 bags and analyzed for moisture content as well. The bags themselves were also inspected for any damage that would have allowed excess moisture intrusion.

4.4.2. Results of Missouri S&T Moisture Intrusion Study. The dust used to fill the bags was sampled and tested (Jan. 13, 2016), and results showed a beginning average moisture content by weight of 0.0428%. Approximately one and a half months later (Mar. 2, 2016), the dust contained in bags labeled 1-7 were sampled and analyzed. This analysis resulted in an average moisture content by weight of 0.0788%, an increase of 69%. It was noted that the contained dust was not caked at this moisture level.

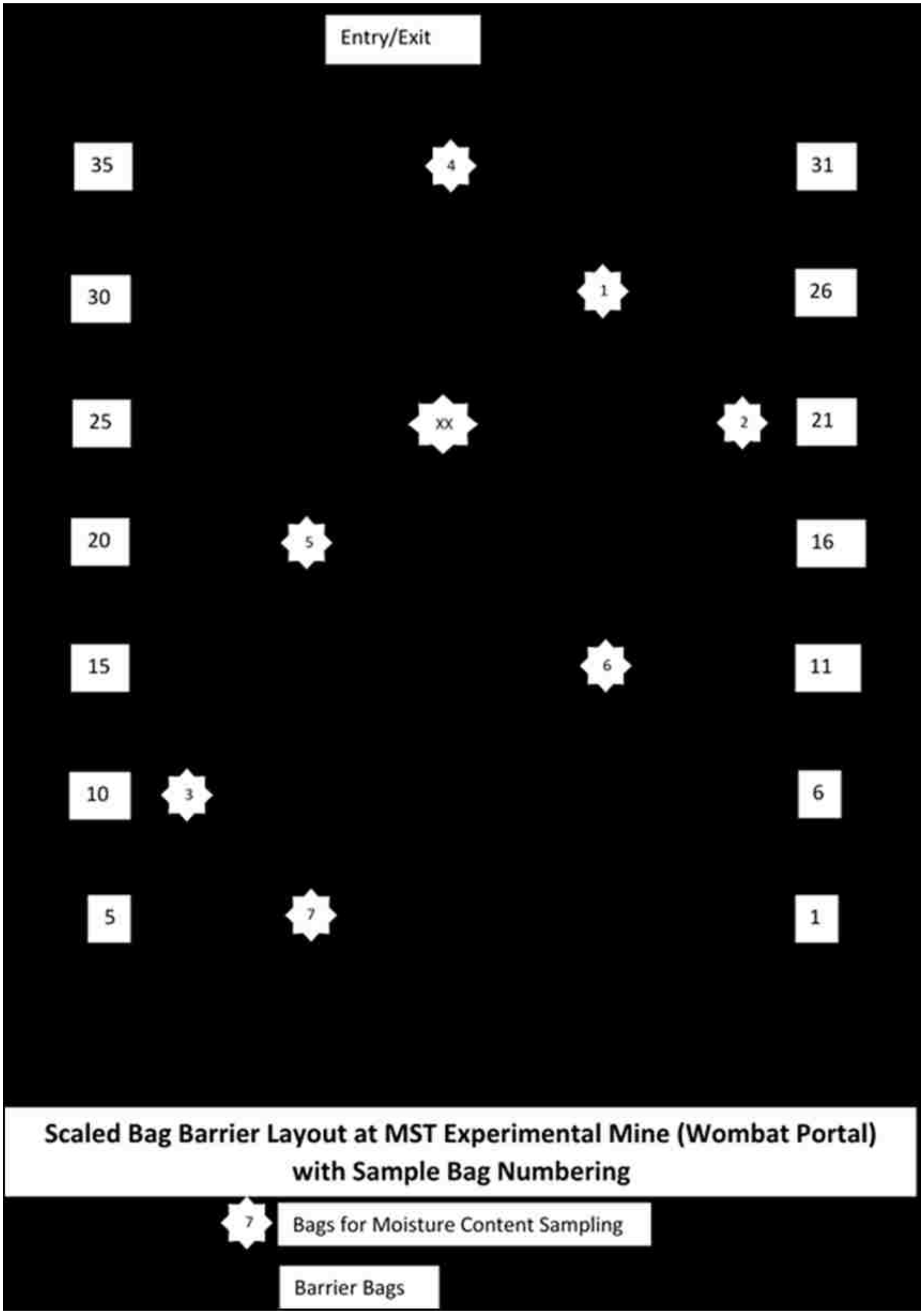


Figure 4.13: Missouri S&T Bag Barrier Layout

Approximately three months later (May 31, 2016), the dust in bags 1-7 was sampled and tested again; resulting in an average moisture content by weight of 0.0724%. It was noted that the dust contained in bag 5 was completely saturated due to a hole in the bag near the retaining ring that allowed water sitting on top of the hook assembly to leak into the bag. Therefore bag 5 results were not figured into the period average. Upon testing it was found that bag 7 had a significantly higher moisture content (3.8684%). It was assumed that this was also due to a hole in the bag allowing water intrusion, and was verified during the next sampling period. For this reason, bag 7 was also excluded from the period average.

Approximately three months later (Sept. 1, 2016), the dust in bags 1-7 was sampled and tested again; resulting in an average moisture content by weight of 1.1656%. Bag 5 was still saturated, and therefore excluded from the period average. Bag 7 was verified to have a hole in the bag near the retaining ring, and the moisture content by weight of bag 7 was 14.2423%. Therefore, bag 7 was again excluded from the period average as an extreme outlier. It is of note that several bags showed a significant increase in moisture content during this period; bag 6 had increased significantly to 4.5946%, bag 3 had increased to 1.2287%, and bag 1 had increased to 0.3581%. It was considered that these bags may have small holes in them near the retaining ring, and was verified during the final sampling. An additional bag that had been undisturbed since the test inception (labeled xx) was also sampled and analyzed, resulting in a moisture content by weight of 0.1054%; a 146% increase by weight since the beginning, but the contained dust was still not caked and was readily dispersible.

At the conclusion of the extended trial, approximately 4 months later (Jan. 4, 2017), the same bags were once again sampled and tested. Bags 5 and 7 had over 16% moisture content by weight and were once again excluded from the period average as extreme outliers. The average of the remaining 5 bags was 1.5626%; however, this value was skewed high by bag 6 which had 6.0225% moisture content. See Table 4.5 for the complete year-long moisture content testing data of the seven test bags.

As previously stated, all bags were sampled and analyzed at the conclusion of the 12-month trial; the results of which can be seen in Appendix G. The overall average moisture content by weight of all 35 bags was 2.3309%. It is important to note that only samples from 9 of the 35 bags (25.7% of the bags) were above 1% moisture by weight after 1 year. Of those 9 bags, the 7 with the highest moisture contents (>6% of the bags) were inspected and found to have holes in the bags near the locking ring which allowed excess moisture into the bags. If these 7 bags that had holes or other damage and excessively high moisture contents are removed from the averaging calculation, the resulting average becomes 0.3670% moisture content. Figure 4.14 is a graphical comparison of the ending (1 year) moisture content of all 35 bags. Figure 4.15 tracks the moisture content of bags 1-7 over the entire 12-month time period.

4.4.3. Analysis of Moisture Intrusion Study Data. The barrier bags were tested against moisture intrusion and contamination of the enclosed stone dust. The long-term testing was performed under extreme temperature and humidity swings due to the trial location in a shallow, short, highly fractured limestone adit portal. It was found through inspection of dust samples during moisture content analysis that the saturation point of the supplied dust is reached at about 16%, and that dust caking was beginning to occur on a limited

Table 4.5: Limestone Dust Moisture Content Analysis over Time

[redacted]

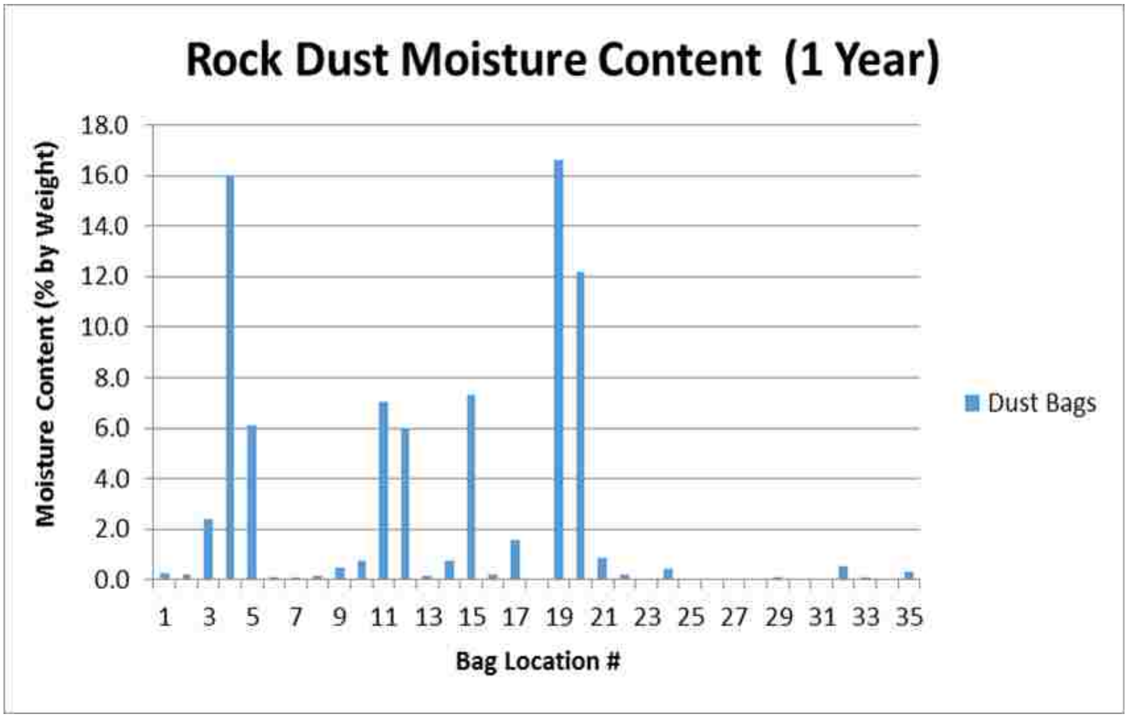


Figure 4.14: Ending (1 Year) Moisture Content of all 35 Bags

basis at just over 2% moisture by weight. Approximately 75% of the bags tested were below 1% moisture by weight. If the 7 bags that were found to be damaged at the end of the testing period are removed from the calculation, the overall average of the remaining dust becomes 0.3670% moisture by weight, which is well below the moisture level required to begin caking. The results indicate positive performance of the bags in conditions worse than would be experienced in an underground coal mine. This indicates that moisture contamination of the rock dust enclosed in the barrier bags is not a concern in a coal mine so long as the bag remains intact. This means that the enclosed dust will not cake and will be readily dispersible when needed to prevent the propagation of an explosion.

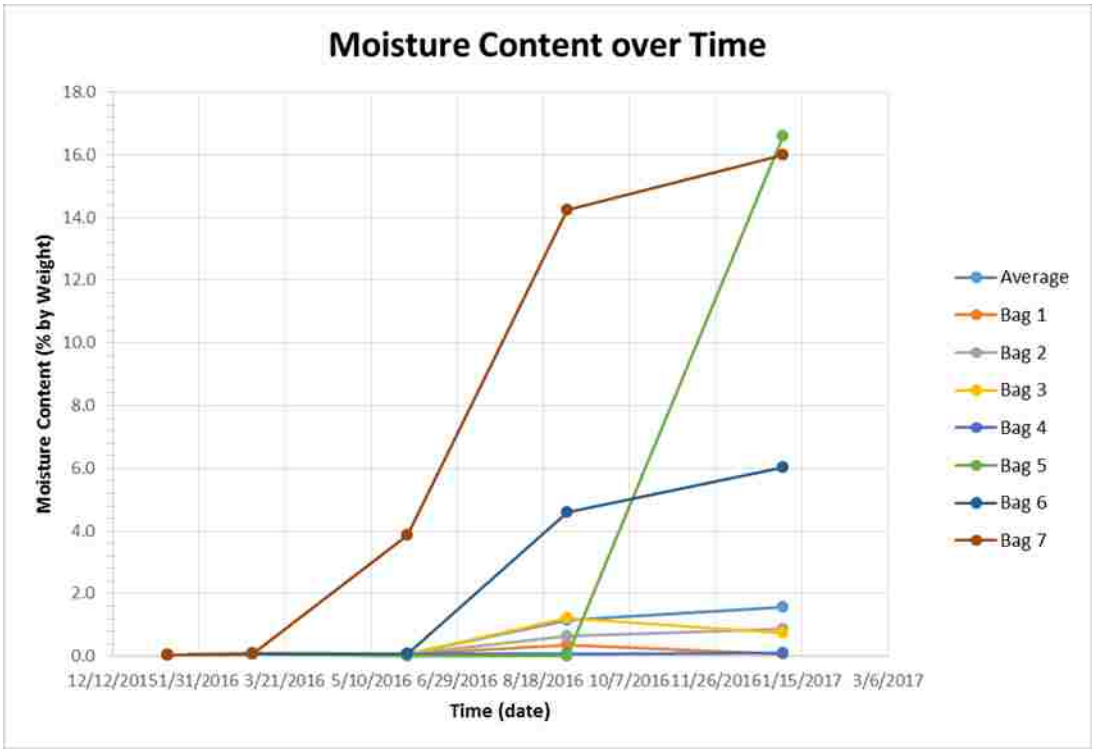


Figure 4.15: Moisture Content over Time of 7 Test Bags

4.5. SUMMARY

Bag Barrier installations were performed in two separate underground coal mines in the Eastern United States. The trials were undertaken to determine whether or not the bag barrier system could be effectively installed in an American coal mine, what difficulties would be experienced, and how could those difficulties be overcome. The two mines used represented differing mining heights and roof support methods, but similar ventilation practices. The mine that used roof mesh on development in all areas experienced no difficulties with installation besides the tall roof height (9 feet) requiring the use of a ladder to hang the bags. The mine utilizing roof straps and bolt plates required the adapting of other supplies (cables, hooks, turnbuckles, clevises, etc.) to provide a method of support for the bags to be hung at the recommended spacing. This would add significant labor and material costs to implement in a full-scale operating mine.

The mine management, engineering, and labor crews at both mines were surveyed prior to the trial bag barrier installation, immediately after the installation was complete, and again after the barriers were in place for four to five weeks. This extended time allowed the mine's crews to work around and interact with the bag barriers. Every miner surveyed stated that they thought more should be done to prevent and mitigate coal dust explosions, yet only 29% of them had heard of the bag barrier system. After helping to install the trial barriers, the miners ranked the bag barrier system a 1.4, on a scale of 1 to 5, in terms of ease of installation. Zero injuries occurred as a result of the bag barrier installations or during their month-long trial, and 86% of miners stated that they would have an improved sense of workplace safety with full scale bag barriers in place. In all, the trial bag barrier installations proved successful, and were a valuable source of information and feedback.

An early concern among the mine site engineering staff was the barrier bags' ability to prevent moisture intrusion and contamination of the enclosed stone dust which would cause the dust to cake or clump together. To investigate this concern, a year-long moisture intrusion study was performed in the Experimental Mine at the Missouri University of Science and Technology, and can be taken as a worst-case scenario. The location in the adit portal close to the surface and equidistant between the portal and ventilation shaft assure wild swings in temperature and humidity. At times there was standing water up to 6 inches deep below the bag arrangement, and water dripping through the mine roof onto the bags like rain due to the fractured limestone cover. These conditions are more extreme than that experienced in a typical deep coal mine. Even still, if only the bags without physical holes or other damage are considered, the dust contained in the remaining 28 bags averaged 0.3670% moisture by weight. Additionally, dust collected and tested from mine sites #1 and #2 contained 0.1435% and 0.1360% by weight of moisture. The results of the year-long moisture intrusion study along with those of the mine site testing indicate that moisture contamination of the rock dust enclosed in the barrier bags is not a concern so long as the bags remain intact and without tears or holes.

5. REQUIRED CHANGES OR IMPROVEMENTS FOR USE OF BAG TYPE EXPLOSION BARRIERS IN U.S. COAL MINES

5.1. OVERVIEW OF REQUIRED CHANGES

There are many technical aspects to be considered, besides installation logistics, in regard to adapting the bag barrier systems currently used in other countries to underground coal mines in the United States. Some of the main points considered here are 1) the effects of mine type and layout differences, 2) coal seam and mining height differences, 3) roof support system differences, and 4) ventilation system differences on the bag barrier system components and barrier configurations and layouts within the mines. Though there are many other site-specific issues and obstacles to consider, they are merely technical obstacles that must be planned and accounted for in the barrier design and placement at each individual site; just as it is done in the many foreign mines that currently employ them. This section outlines the primary considerations for implementing the bag barrier system into American coal mines, and makes suggestions for their installation based on previous research, operating mine site trials in the U.S., and explosives tests to understand the operational characteristics of the bags themselves.

5.2. BAG BARRIER SYSTEM LAYOUT OR DESIGN CHANGES

The principles of coal dust explosions are similar in U.S. and foreign mines alike. Additionally, the bag barrier system design in each country utilizing them is based off the same research and testing performed at the Kloppersbos, Tremonia, and NIOSH Lake Lynn underground experimental mine testing facility in the United States. Therefore, many of the design characteristics for bag barrier installation in the U.S. can be adapted from installation guidelines currently used in foreign nations. However, the U.S. does utilize distinctive mine layout and ventilation schemes that could cause changes to the typical bag barrier system installations and designs employed elsewhere. The following subsections discuss the areas in which the bag barrier system may differ between installation in the U.S. and other countries; as well as proposing which design aspects the U.S. is likely to copy from the foreign nations.

5.2.1. Coal Seam and Mining Height Differences. While there are many differences between the underground coal mines in countries that currently use bagged stone dust explosion barrier systems and U.S. mines, none were discovered that would prevent the successful implementation or operation of the bagged stone dust barrier system in its current form. That is, aside from mines with very short seam and roof heights, which physically preclude them from accommodating a bagged stone dust explosion barrier system due to the length of the hook and bag system. Similar to foreign mines with greater mining heights or roof cavities, American mines would also require additional layers of barrier bags to be installed in these instances.

Typically, U.S. mines have much lower average opening heights than mines in NSW, the UK, and the RSA. Since the required stone dust loading for a bag barrier is based on the cross-sectional area of the mine entry in which the barrier is installed, American coal mines may require fewer bags. However, the potential for these savings are limited since current NSW, RSA, and UK guidelines have limitations on the maximum spacing between bags and the minimum weight of rock dust per bag. Potential also exists that low mine heights may render the bag barrier system installation futile if heights are low enough to guarantee damage to the barrier bags from moving equipment and personnel. It is possible that adjustments may be made to the barrier design to accommodate mines with lower opening height. Some of these possibilities are:

1. Concentrate barrier bags towards the ribs, with a large gap between the bags in the center, to provide a full height roadway and limit damage to the bags from equipment movement.
2. Load bags with more rock dust near the rib and less in bags near the center, allowing shorter bags in the center.
3. Load all bags with less dust (thereby reducing bag hanging height across the entire roadway) and hang rows closer together to maintain proper stone dust loading.
4. Design shorter bags with less airspace to be used in mines with lower seam height.

Research has not been performed to evaluate the effects of any such changes on the coal dust explosion mitigation performance of the bag barrier system, and none of these changes should be implemented until further research has been performed and proven that the bag barrier system remains effective in these altered configurations.

5.2.2. Roof Support System Differences. Roof support requirements in coal mines vary throughout the world. Some locations and regulatory regimes require roof mesh everywhere in a mine; while others leave the decision as to which method of support to use, and where, up to that specific mine or inspector. This disparity in roof support methods, and that of labor costs worldwide, has given rise to two common methods for barrier installation in those nations that use them. The first method is to use existing roof support materials (roof mesh, roof bolt plates, roof straps, etc.) to hang the barrier bags from, leaving them in place and installing new bags on the advancing end of the barrier as mining progresses. In many nations this is easily performed as roof mesh is required throughout the mines. This method requires purchasing a greater supply of bags and stone dust, but it is less labor intensive since the bags are never repositioned once they are hung. The second method of bag barrier installation utilizes separate movable stands for each row of barrier bags to hang from. As mining progresses the farthest movable stand is relocated to the front of the barrier closest to the mining face. Additional stands would be required for extra tall mines or roof cavities requiring additional layers as described in the previous section. This method reduces overall material costs by requiring considerably less bags and stone dust, though it is much more labor intensive.

Unlike NSW where roof mesh is required throughout the mine, the United States is similar to RSA and the UK only requiring roof mesh where it is necessary. However, comparable to NSW and the UK, the labor costs in the United States are relatively high. Therefore, it is anticipated that U.S. coal mines would choose to install bag barriers using the first method of installing additional bags as opposed to moving existing ones. Unfortunately, U.S. mines that do not currently install roof mesh will have additional expenses to install roof mesh where needed for barrier installation, install additional roof bolts for proper bag spacing, or develop an appropriate and more cost-effective alternative system for hanging the bags at the required spacing.

5.2.3. Mine Type and Layout Differences. Mining methods are one of the primary differences between underground coal mines in the U.S. and the other nations that use bag barriers. In the U.S., room-and-pillar mines are similar in number to longwall mines, and are both often found in different areas of the same mine. In the UK and NSW, room-and-pillar mines are virtually non-existent. In the RSA, room-and-pillar mines makeup a majority of the mines. The room-and-pillar mining method results in a significantly larger area of open workings because there are a greater number of entries in each panel, submain, and main tunnel. The greater number of entries is necessary for both increased extraction and ventilation purposes. Therefore, room-and-pillar mines that wish to install bag barriers will have more entries to cover with bag barriers, meaning a greater supply of bags and stone dust must be purchased. This required supply of barrier materials will be even greater if the mine decides to leave the bags hanging in place and add additional bags as mining progresses. In longwall mining, much of the mined-out area is immediately covered by the gob and open workings are reduced to a minimum. This also reduces the supply of barrier materials required.

In NSW, barrier installation is only required in ventilation returns and belt entries, though it is recommended that mines installing the bag barrier system use a risk-based approach to evaluate the necessity of placing additional barriers in other entries as well. Assuming that an American coal mine has decided to install a complete bag barrier on the pre-existing room-and-pillar panel shown in Figure 5.1; the blue shaded areas in the entries are the required bag barrier locations according to regulations and guidelines used in NSW. The start and end locations of the barriers must be maintained within certain distances from the face, so additional bags will be installed inby as mining progresses. For this mine, entry A is the return, entry B contains a conveyor belt, and entry C is the fresh air intake. According to NSW regulations, barriers are only required in entries A and B, not in the intake (entry C). In NSW, individual mines will decide if they want to place barriers in the intake entries or other areas of the mine. Since barriers are not currently mandated in the U.S., individual mines may also make this decision for their mines.

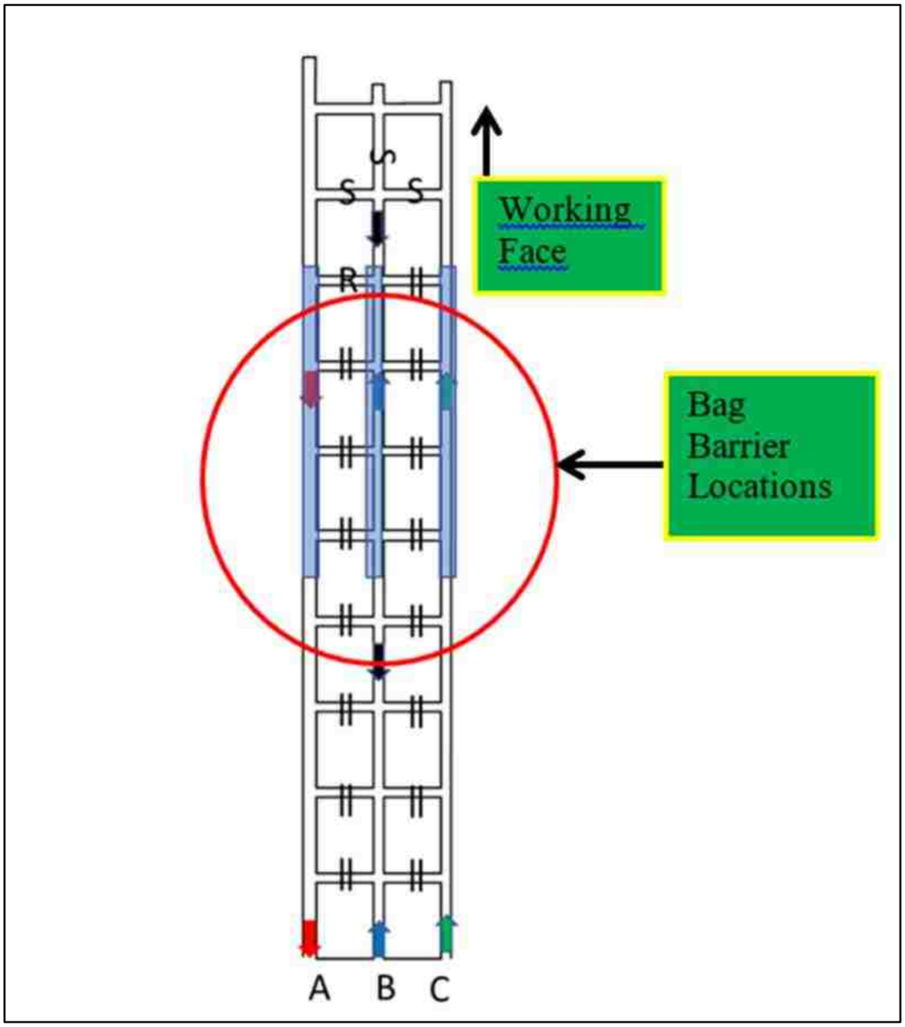


Figure 5.1: Bag Barrier Locations for an Example Room and Pillar Mine

Unlike room-and-pillar mines, longwall mines are more likely to place bag barriers in all entries. This is because a longwall panel’s development section on the headgate side (intake) becomes the tailgate side (return) of the next adjacent panel.

Therefore, it is generally easier to install the barrier in all panel development entries including intake entries. Assuming that a U.S. mine has decided to install a bag barrier on the pre-existing longwall panel with one bleeder, shown in Figure 5.2; the blue shaded areas in the entries are the required bag barrier locations according to regulations and guidelines used in NSW. The start and end locations of the barriers must be maintained within certain distances from the face, so additional bags will be installed outby as mining progresses. For the development section on the headgate side at this mine, entry A is the return, entry B is the intake, and entry C has a conveyor belt. According to NSW regulations, barriers are only required in entries A and C, not in the intake (entry B). On the tailgate side however, entries A, B, and C are all returns, and each of these entries require barriers. However, if another longwall panel will be created to the left side of this panel, then the headgate for this panel will become the tailgate for the next panel.

5.2.4. Ventilation System Differences. There are two primary differences between ventilation systems in the U.S. and those in NSW, the UK, and the RSA. The first regards longwall panel ventilation. In most U.S. longwall mines, bleeder systems are used which have entries at the inby end of the panel behind the gob, as seen in Figure 5.2. NSW and UK mines almost exclusively use U-system ventilation schemes, which do not have these additional bleeder entries. RSA mines use various ventilation systems, though bleeder systems are rare. It is possible that U.S. mines may be required to protect the bleeder entries in addition to areas normally protected, which would be an additional cost not seen in the other nations that do not utilize a bleeder system. Figure 5.3 shows the scenario for the mine in Figure 5.2 if that mine had chosen to install bag barrier systems to protect the bleeder entries as well. Note that the working face is close to the bleeder

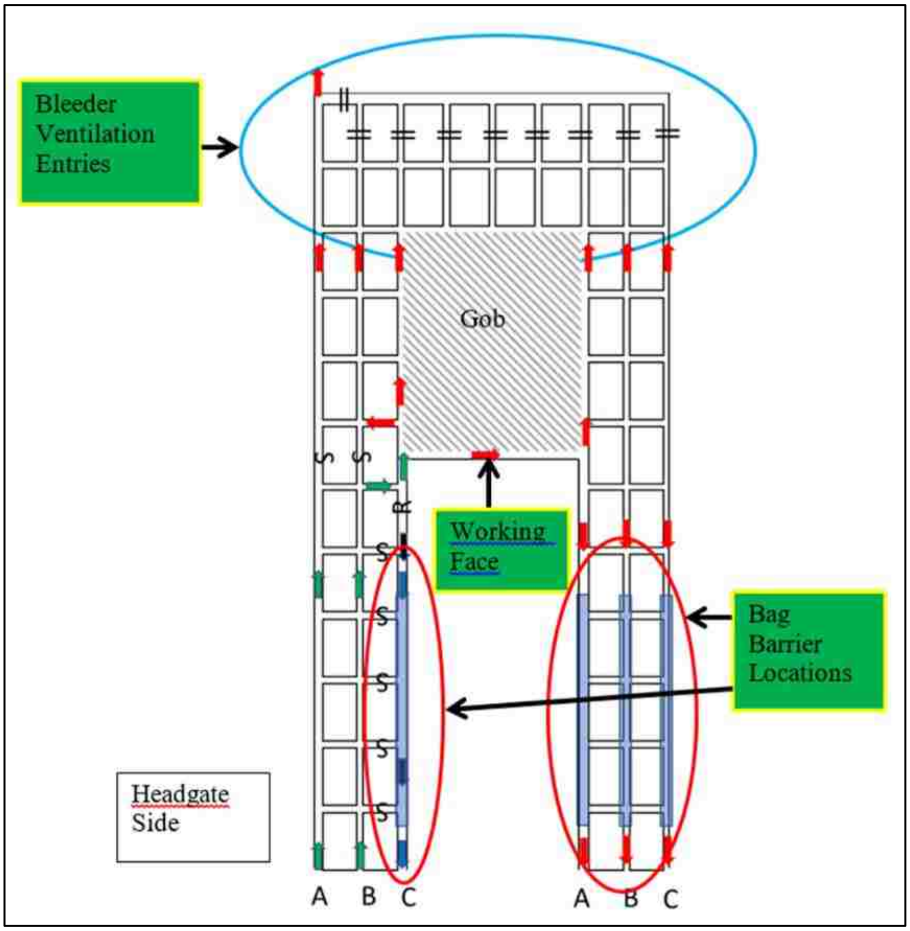


Figure 5.2: Bag Barrier Locations for an Example Longwall Panel

entries, which does not allow adequate distance to complete the required length for the barrier. Therefore, the barrier is split, and the additional required length is continued in each adjacent entry or crosscut for the panel. For future panels, production begins at the inby end of the panel, which means protecting the bleeder entries will require bags to be installed in all entries in the bleeder area and all crosscuts adjacent to the gateroads. Installing a bleeder protecting barrier on an existing mid-production panel would require installation inby the working face, which is generally considered dangerous and workers are not allowed in these areas. In the interest of safety, this mine may decide instead to avoid barrier installation on this panel, and to hang bags for future panels throughout the headgate and bleeder entries and crosscuts during further development.

The second difference between the U.S. and NSW, UK, and RSA mine ventilation schemes is the neutral airway. In the U.S., the belt is required to be in neutral airways, but neutral airways are not required at all in these other three nations. This means that the U.S. will have at least one additional entry in each longwall panel to install barriers in compared with these three other nations. According to current guidelines barrier installation is only necessary in the returns for mains, submains, and room-and-pillar panels; though it is recommended to install barriers in all entries. If U.S. mines choose to install in all entries, U.S. mines will have at least one additional entry to install bags in all portions of the mine.

5.3. SUMMARY

There are many technical aspects to be considered, besides installation logistics, in regard to adapting the bagged stone dust barriers currently used in other countries to underground coal mines in the United States. However, aside from mines with very short seam and roof heights, which physically preclude them from accommodating a bagged stone dust explosion barrier system due to the length of the hook and bag system, all of the other impediments to adapting these barrier systems to U.S. coal mines are merely technical obstacles that must be planned and accounted for in the barrier design and placement at each site; just as it is in the foreign mines that currently employ them. If used as outlined in other countries, the differences in ventilation practices and mining methods utilized in the U.S. would require additional bag barriers due to the use of additional neutral airway entries.

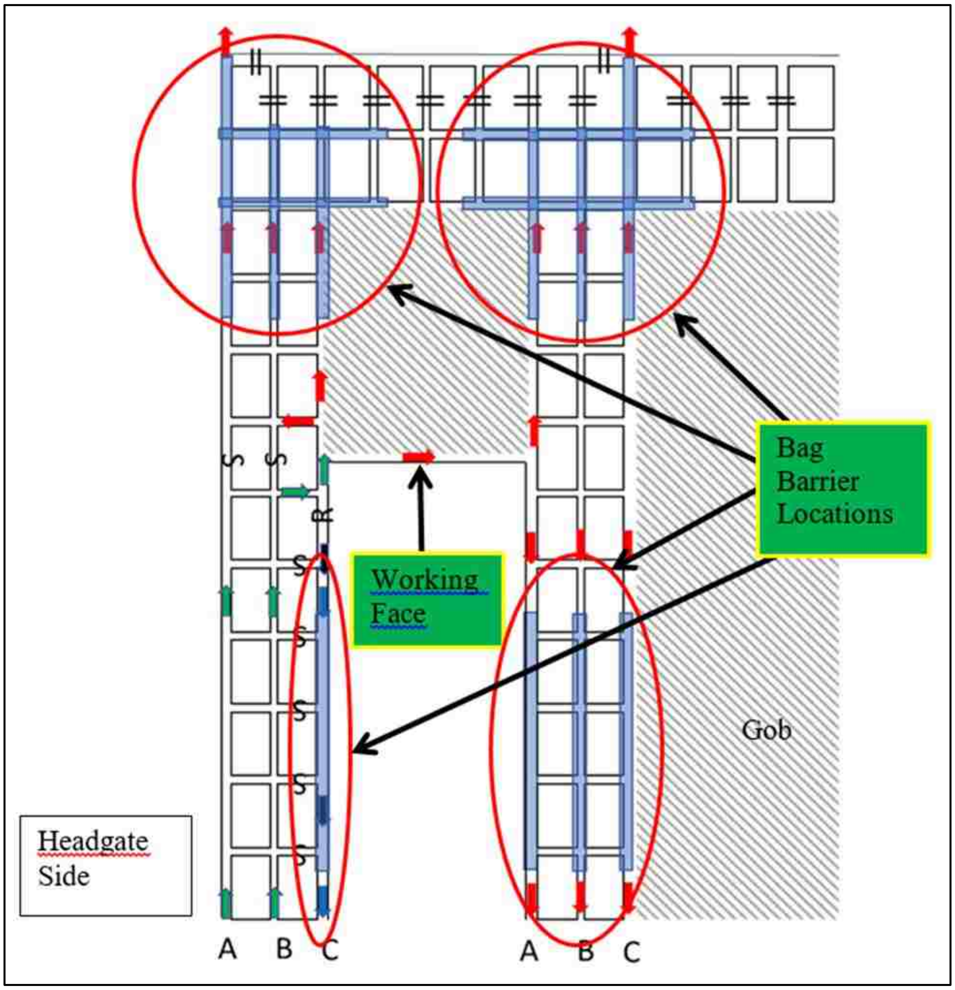


Figure 5.3: Bag Barrier Locations for an Example Longwall Panel, Including Bleeder Barriers

Additionally, the greater number of entries utilized for room and pillar mining methods in the U.S. would require additional bag barriers. These additional barrier requirements would presumably come with an increased cost. That is, unless further research would uncover ways to optimize the bag arrangements, spacing, or loading for the generally smaller mine entries in the U.S. which could reduce costs. It is recommended that a risk-based approach be taken with determining the most appropriate locations for the installation of barrier systems in each mine.

6. CONCLUSIONS AND IMPACT ASSESSMENT

6.1. PROJECT OVERVIEW

The most significant and powerful hazard that exists in an underground coal mine is a coal dust explosion. A coal dust explosion has the potential to propagate to every part of a mine resulting in massive damage to the mine and equipment, as well as tragic loss of life. Since the beginning of coal mining in the U.S., thousands of lives have been lost to coal mine explosions. More recently, disasters due to coal dust explosions in U.S. underground coal mines have caused 59 deaths since 2001; including 29 deaths in a single mine explosion at the West Virginia Upper Big Branch (UBB) mine in 2010. In the same time period since 2001, in NSW, RSA, and the UK there have been no deaths attributed to coal dust explosions at all. The primary and most significant difference in safety standards between the U.S. and the others during this time is the mandatory use of explosion barriers by the other countries. The lack of explosion deaths in foreign coal mines since the implementation of explosion barriers demonstrates the positive impact the barriers have had in foreign mines. It is therefore theorized that the U.S. mining industry could also benefit from reduced coal mine explosion deaths due to the implementation of explosion barriers in underground coal mines in the United States.

Prior to the mandatory implementation of explosion barriers in U.S. mines, similar to the bag type barrier, a greater understanding of their operational requirements and limitations are needed. This project brought together coal mining industry leaders, researchers, and regulators to begin dialogue regarding the possible implementation of the bag type passive explosion barrier system into U.S. coal mines in the future. These conversations centered on various aspects of importance to begin the evaluation of the product and its application. Of decidedly high importance were the operational characteristics of the bags themselves to various shock and pressure stimulus. In addition, long-term moisture contamination of the stone dust contained within the bags was of concern. Finally, the logistics of actually installing the bag barrier systems in U.S. coal mines, along with the durability of the bags to withstand the rigors of daily mining operations was of significant interest. This project addressed these issues individually, having a significant impact on the future research and possible implementation of the bag type passive explosion barrier system in U.S. coal mines.

6.2. PROJECT IMPACTS

This research project was comprised of 3 main objectives. Each objective had specific impacts that positively affected the outcome of the project goals. The completion of each objective was also required to support the goals of this thesis. The following three sections outline each objective and their related impacts.

6.2.1. Objective 1: Operation of Bag Type Passive Explosion Barriers. The purpose of Objective 1 was to understand the principle operational characteristics of the bag type passive explosion barriers. This was needed so that nothing in the fundamentals of operation of the bag barriers would be overlooked in their application and implementation into the diverse and dynamic environments found in U.S. The operation of the barrier bags was divided into two main categories, or actions. The first of which is the actual tearing or rupturing of the anisotropic bags. The second being the dispersal of the contained stone dust. Both are required to extinguish a developing coal dust explosion; however, these two operational aspects are of different genesis.

To clarify the difference between the forces acting to tear or rupture the bags and those acting to disperse the contained stone dust, two experimental tests were designed and completed. To differentiate between the pressure required to rupture the bag and that necessary to disperse the contained rock dust, one testing parameter was changed. One set of tests were performed in open air. The second set of tests were performed in a fabricated rectangular shock tunnel to simulate the confinement and focusing of the explosion impulse, similar to that which occurs naturally in an underground mine working. The results of the open-air testing revealed that the damage to the barrier bags is reliant on a combination of pressure and impulse, and can be broken down into 4 distinct regions. The first pressure-impulse region is an unbroken bag region, no bags were broken in this area of pressure and impulse. Second was a transition region where some bags break and some do not. The third area was a broken bag region, where all bags tested broke. Finally, a shredded bag pressure-impulse region in which the bags tested were completely shredded. Additionally, during the open air testing the contained stone dust was only dropped from the ruptured bags, but not dispersed, and only at the highest shock pressure levels. Furthermore, the open-air testing results show that the bags begin to tear or rupture at higher pressures than that reported by the bag barrier system distributors.

The confined tunnel tests displayed complete rupture or tearing of all bags tested, and incrementally greater degrees of dispersal of the contained stone dust with higher impulse values. The results of these tests indicate that the barrier bags do not operate (tear and disperse) on pressure alone, and demonstrates the importance of the explosion impulse on dispersal of the contained stone dust and the subsequent extinguishing of a developing coal dust explosion. These discoveries will have a great impact on the understanding of principle operation of the barrier bags and the future testing and development of alternative products and methods.

6.2.2. Objective 2: Implementation of Bag Type Passive Explosion Barriers in U.S Coal Mines. Objective 2 allowed for interaction with mine site executives, engineers, and laborers while experiencing the finer points of barrier installation under two different sets of mine conditions. Of significance is the fact that one mine utilized roof mesh on development in all entries; and the other roof bolted, and only used mesh where needed. The bag barrier installation at the mine with roof mesh was very straight-forward with the bags hanging directly on the mesh from their included hook. This method allowed for a large degree of adaptability and spacing options. The roof bolted mine required some additional work and site devised alternative support methods to allow hanging the bags at the correct spacing. Alternatively, the roof bolt spacing could be reduced, and an extra bolt placed in each row, to allow for hanging the bags at the correct spacing, directly from the roof bolt plates.

In either case, the installations were completed successfully, with adequate personnel and equipment clearance, and left in place for 5 weeks. This time allowed for mine development past the barriers, and miner and equipment interactions with the barriers. The miners and engineering staff were surveyed prior to barrier installation, immediately following the completion of barrier installations, and again upon return to the mines after 5 weeks to sample and remove the barriers. The preliminary surveys indicated that 100% of the miners were familiar with recent mine explosion disasters and the risks of explosions in coal mines, and that more should be done to prevent such disasters. However, only 21% of the miners were familiar with the bag type explosion barrier system. The post-installation survey revealed that miners thought the barrier system was easy to install (1.4 on scale from 1 to 5), and that 86% of the miners claimed they would have an improved sense of workplace safety with a full-scale explosion barrier system in place. The follow up visit surveys showed that no injuries occurred as a result of the barrier bag arrangements. The miners reported some experiences with the barrier bags such as they were too easy to break, they hung too low, and were in the way when laying track, moving power cables and piping, or unloading equipment from rail cars.

The contamination of the dust enclosed in the bags by moisture was of high interest. A year-long moisture intrusion study was performed in the Experimental Mine on the campus of Missouri University of Science and Technology. A supply of stone dust was tested for moisture content, then bagged and hung in the mine adit. The dust in the bags was periodically tested for moisture content throughout a year’s time. Additionally, the dust from the barrier bags used in the mine site trial installations was tested. The campus test was seen as a worst-case scenario since the location of the bags in the adit was prone to wild swings in temperature and humidity that would not likely be experienced in a deeper underground mine complex with constant ventilation flow. Furthermore, there were periods when there was standing water below the barrier arrangement due to the inflow of water through the highly fractured limestone roof in the mine portal. The results of this study indicate that the contamination of the contained stone dust by moisture intrusion is not a concern, so long as the bags remain intact and without holes. Bags that acquire holes, and become contaminated with moisture, can be easily spotted upon visual inspection and replaced if needed.

The outcomes of Objective 2 are significant for many reasons. First, it proves that the bag type explosion barrier system can be implemented into different underground U.S. coal mines with minor modifications as required for mine site-specific concerns. This is similar to the numerous minor adjustments required by the multitude of foreign mines that utilize this technology. It also indicates that miners think the system is easy to install and that they would have an improved sense of workplace safety with explosion barriers in place. A deep held concern for the contamination of the enclosed stone dust by moisture intrusion was also addressed and shown to be a non-issue. These items address many concerns expressed by industry leaders, researchers, and regulators when discussions began regarding the possible implementation of the bag barrier system into U.S. coal mines. These discoveries lay the groundwork for future studies by eliminating some preliminary obstacles and answering some fundamental questions.

6.2.3. Objective 3: Required Changes or Improvements for Use of Bag Type Explosion Barriers in U.S. Coal Mines. There are a large number of differences from one coal mine to another, not to mention the differences between mines in different regions or countries. Aside from the technical differences, there are other aspects to consider as well. However, excepting mines with very short seam or roof heights, which physically preclude them from utilizing bag barriers due to the hanging length of the bags, all of the other impediments to adapting these barrier systems to U.S. coal mines are merely technical obstacles that must be planned and accounted for in the barrier design and placement at each site; just as it is in the foreign mines that currently employ them. In view of this, there are no specific improvements required to implement the bag barrier passive explosion mitigation system into U.S. coal mines.

Some design or layout changes may be required to implement this system into U.S. mines due to the difference in ventilation and mining practices. For example, more bags in more locations are required for room and pillar mines versus longwall mines due to the additional entries and large openings required for this type of mining. Additionally, U.S. longwall mines use a minimum of three entries per gate road (intake, return, and neutral or belt road), while foreign longwall mines typically use two entries. This also requires additional barriers and bags. The use of bleeder entries in U.S. longwall mines yields the need for additional barrier locations to protect those from possible explosion propagation as well.

While there were no technical obstacles uncovered that would prevent the implementation of the bag barrier system into U.S. coal mines, this study did uncover many differences that need to be researched further. Many of these differences will be site specific factors that must be carefully considered, organized, researched, accounted, and planned for in the selection of barrier placement and design. This is a similar process to that which is used by each mine that is required to employ explosion barriers in every foreign country that requires them. Therefore, bag barrier implementation becomes an economic evaluation of the technical costs of implementation at each independent mine site.

6.3. PROJECT CONCLUSIONS

The main goals of this project were to introduce a well-tested and widely utilized (internationally) explosion mitigation strategy to the U.S. coal mining industry, and to instigate conversations between coal industry researchers, regulators, and producers regarding the need for additional safety measures concerning explosion risks in U.S. underground coal mines. In the simplest context, these goals were accomplished through:

- Explosive testing of the barrier bags that when plotted on a pressure-impulse diagram clearly define the pressure sensitive and dynamically sensitive regions of damage for the bags, and highlights their operational characteristics for further study.
- Long-term moisture intrusion study of the bags under extreme conditions of temperature and humidity swings indicate that no significant moisture intrusion into the bags occurs, the enclosed dust remains dry with no caking, and therefore dust dispersal will not be affected by bag use in wet, humid coal mine environments.
- Trial installations of bag barriers in operating coal mines in the Eastern United States that prove their implementation is feasible in most medium height coal mines in the U.S.
- Surveys of miners before and after the bag barrier installations in their mines, and after a month of working around the bag barriers indicate that they understand the explosion risks inherent to coal mining and would like to see more safeguards in place to prevent them. Additionally, the miners liked the bag barrier system and felt safer with them in place.

The introduction and regulation of explosion barriers in the United States is a very dynamic subject requiring multi-faceted analysis. These analyses must be continued beyond the scope of this project for the full impact of this project to be realized. It is understood that the American regulatory system does not provide for a risk-based approach to the management of hazards in coal mines. However, based on the multi-national use of a proven explosion mitigation system implemented via risk based assessments, the feedback received from U.S. miners that indicates their desire for additional safeguards against explosion hazards, and the results of the testing performed here that outlines the operational characteristics of the barrier bags, it would seem prudent for MSHA to at least allow the use of this additional layer of defense against coal mine explosions. In the absence of specific legislation regarding the implementation and required installation locations of explosion barriers in U.S. mines, a risk based approach is the only applicable method for interested mines to implement the bag barrier system and utilize this extra layer of protection in their mine.

In closing, the words written in the 1928 USBM Report 277 by a coal dust explosion research pioneer, George S. Rice of the U.S. Bureau of Mines, still ring true today. He stated, “Although everyone hopes that the employment of all known preventative methods will minimize the mine explosions and fires that entrap men, no mine operator is justified in assuming that no unusual occurrence, careless act, or mistake will ever cause a disastrous fire or explosion in his mine.” On this account it is advisable to employ any and all means necessary to prevent coal dust explosions and their destruction in the United States as it is in other countries. The allowed implementation of the widespread use of explosion barriers in coal mines in the United States as an assurance against the unthinkable failure of the other methods of prevention, or the intentional or mistaken act of a miner or mine operator, should be re-evaluated on a risk-based approach.

6.4. RECOMMENDATIONS FOR FUTURE WORK

To continue this work and further the understanding and implementation of explosion barriers in underground coal mines in the U.S., further research is recommended. Many questions arose during this project that were outside the scope of this project. This gave rise to many additional areas of research interest. The areas of this future research should include:

- The appropriate location/placement of passive and active explosion barriers in U.S. mines based on disaster reports and coal dust fallout survey data
- Active explosion barrier alternatives, and active explosion barrier triggers, suppressants, and dispersion apparatus.
- The applicability of incorporating explosion barrier systems with in-mine monitoring and communication systems
- Do mines with shorter seam heights need the same distance to the first row of bags, since in shorter seam mines the pressure wave and flame front may behave differently?
- Can short seam height mines concentrate the bags towards the ribs to save space in the center of the roadway for equipment clearance?
- Can the bag height be reduced by having less air-space or contained dust and bag row and spacing be closer together to compensate?
- Is there a concern with the flammability of the bags and is further testing required to satisfy MSHA?
- Are the bags an additional area for dust collection or ventilation impedance?

APPENDIX A.

MATERIALS AND EQUIPMENT UTILIZED IN OPEN AIR TESTING OF BARRIER BAGS

The contents of Appendix A. include a listing of the equipment and materials required to complete the 60, 120, and 240-gram C4 open-air testing of the barrier bags at the Missouri S&T Experimental Mine Facility's Blast Test Pad.

- PPE (Hard Hats, Safety Glasses, Hearing Protection)
- Digital Camera
- Remote Trigger Box and Interface Cable
- Data Acquisition System
- 6 Piezoelectric Pressure Transducers
- 6 Pressure Transducer Coax Cables
- 6 Pressure Transducer/Bag Hanger Stands
- 6 Stand Weight Buckets
- 24 Skillpro Stone Dust Bags
- Charge Hanging Stand
- 2 Power Extension Cords
- Scorpion Initiation Box
- Blasting Cable Reel
- Trigger Cable Reel
- 1 Roll Wire – Charge Hanging
- Extra Electrical Wire for Cap Mounted Triggers
- 1 Roll Electrical Tape
- Tape Measure
- Table
- #8 Blasting Caps (electric) – Qty:3

- 60-gram Spherical C4 Charge – Qty:1
- 120-gram Spherical C4 Charge – Qty:1
- 240-gram Spherical C4 Charge – Qty:1
- 2 Barricades and Warning Signs
- Phantom High-Speed Camera and Tripod
- Laptop Computer

APPENDIX B.

PRESSURE TRANSDUCER WAVEFORMS AND GRAPHS

The information contained in Appendix B. includes a screen shot of the actual Synergy Data Acquisition System pressure transducer waveform for the 60, 120, and 240-gram C4 open air tests. Additionally, individual pressure versus time graphs for each of the six pressure transducer locations and distances are given for each test. Figures B1 - B1.6 contain pressure versus time graphs from the 60-gram C4 test; Figures B2 - B2.6 contain them for the 120-gram C4 test; and Figures B3 - B3.6 contain them for the 240-gram C4 test.

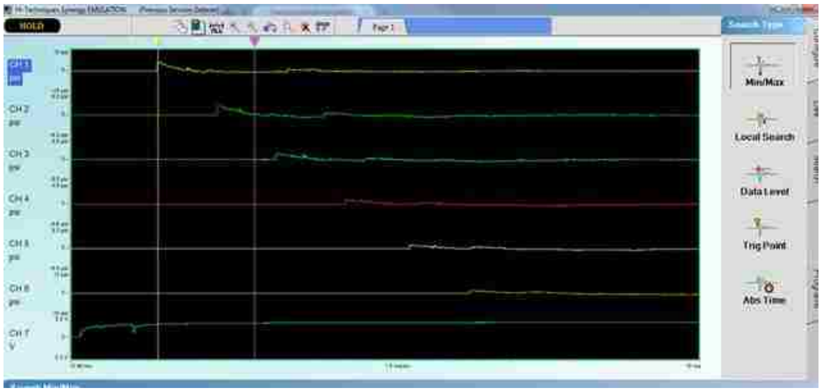


Figure B1: 60-gram C4 Charge Pressure versus Time Waveforms

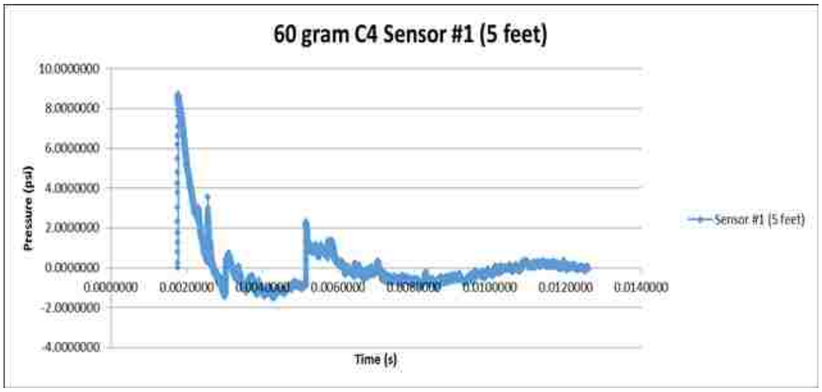


Figure B1.1: 60-gram C4 Charge Pressure versus Time Graph Sensor #1 (5 feet)

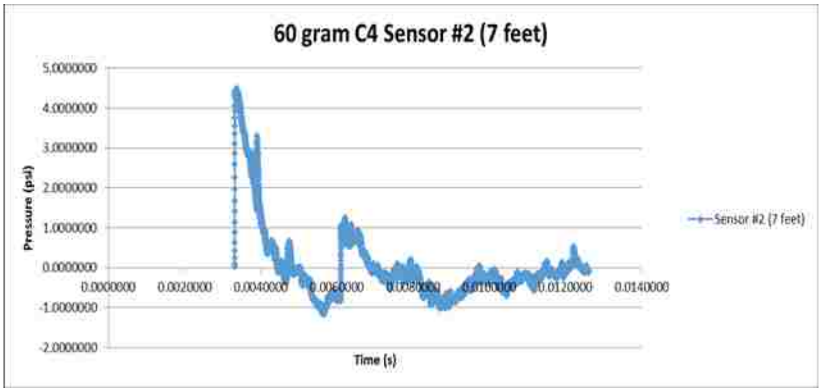


Figure B1.2: 60-gram C4 Charge Pressure versus Time Graph Sensor #2 (7 feet)

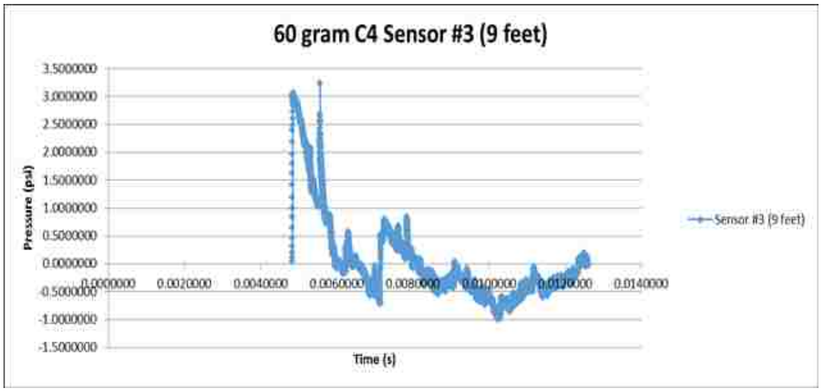


Figure B1.3: 60-gram C4 Charge Pressure versus Time Graph Sensor #3 (9 feet)

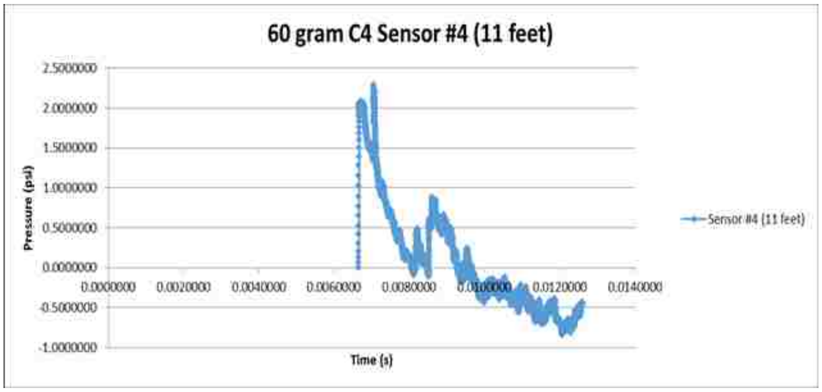
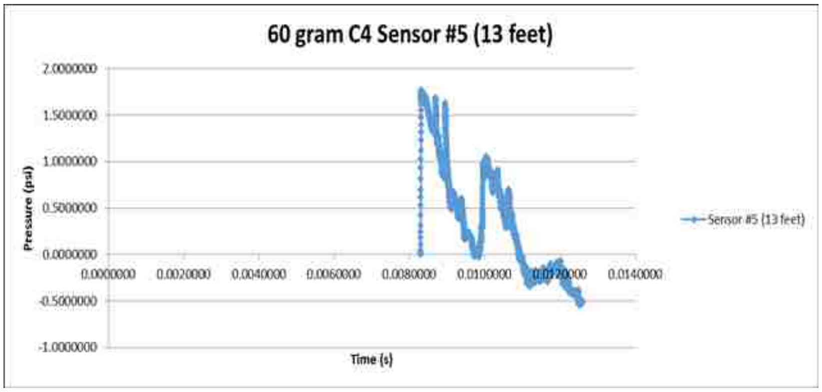


Figure B1.4: 60-gram C4 Charge Pressure versus Time Graph Sensor #4 (11 feet)



B1.5. 60-gram C4 Charge Pressure versus Time Graph Sensor #5 (13 feet)

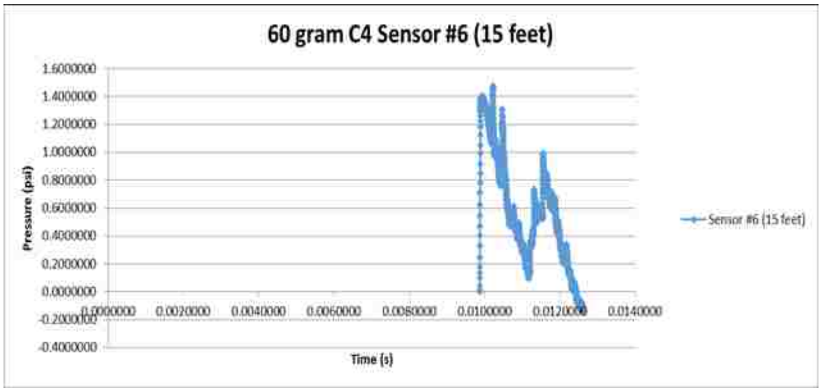


Figure B1.6: 60-gram C4 Charge Pressure versus Time Graph Sensor #6 (15 feet)

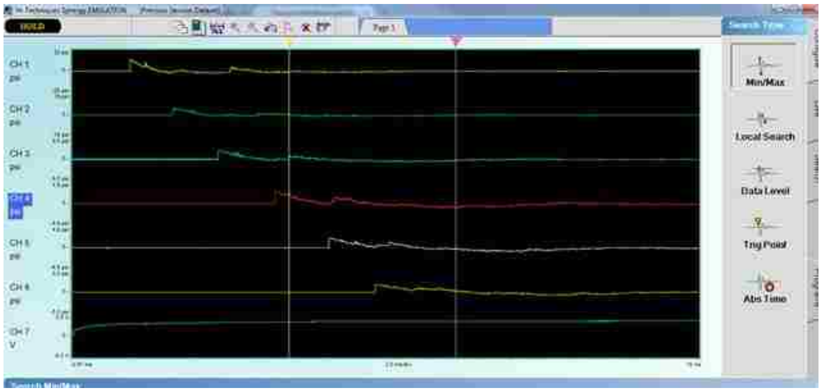


Figure B2: 120-gram C4 Charge Pressure versus Time Waveforms

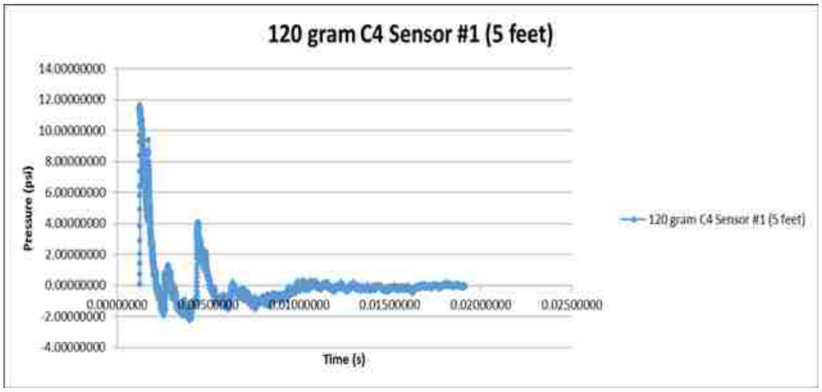


Figure B2.1: 120-gram C4 Charge Pressure versus Time Graph Sensor #1 (5 feet)

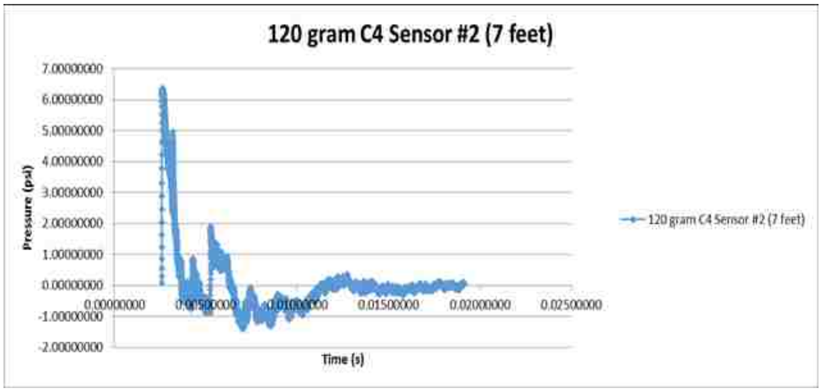


Figure B2.2: 120-gram C4 Charge Pressure versus Time Graph Sensor #2 (7 feet)

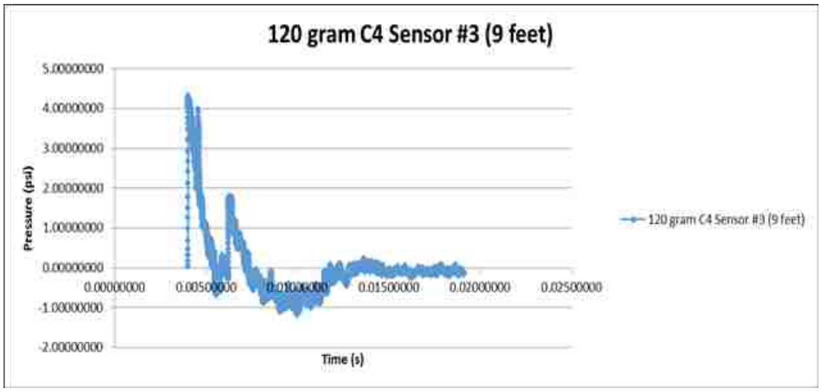


Figure B2.3: 120-gram C4 Charge Pressure versus Time Graph Sensor #3 (9 feet)

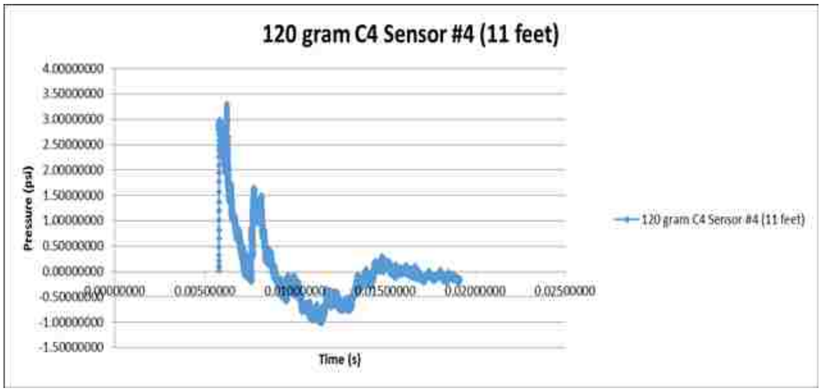


Figure B2.4: 120-gram C4 Charge Pressure versus Time Graph Sensor #4 (11 feet)

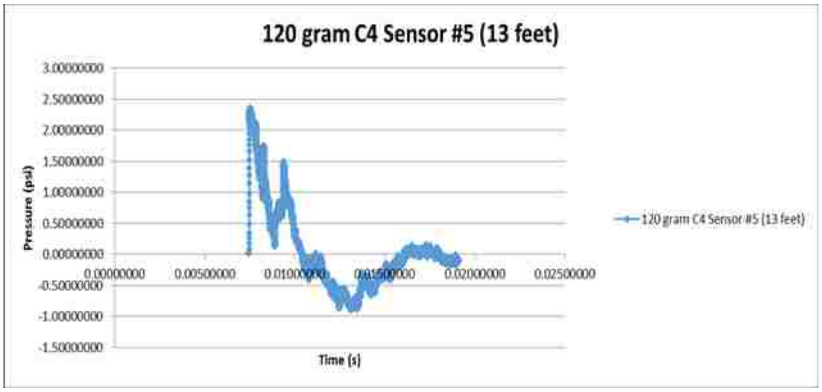


Figure B2.5: 120-gram C4 Charge Pressure versus Time Graph Sensor #5 (13 feet)

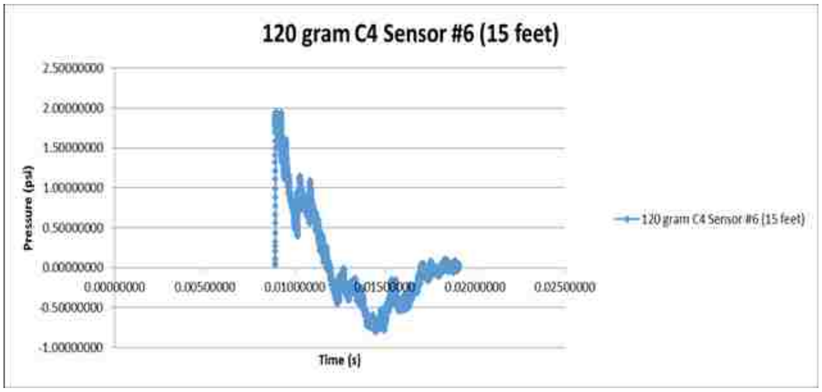


Figure B2.6: 120-gram C4 Charge Pressure versus Time Graph Sensor #6 (15 feet)

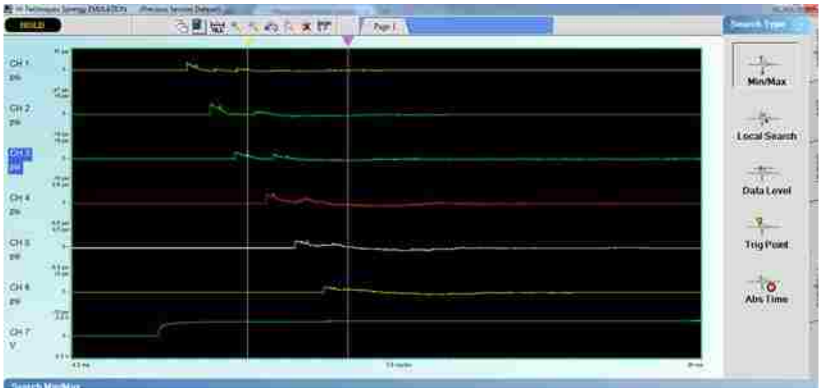


Figure B3: 240-gram C4 Charge Pressure versus Time Waveforms

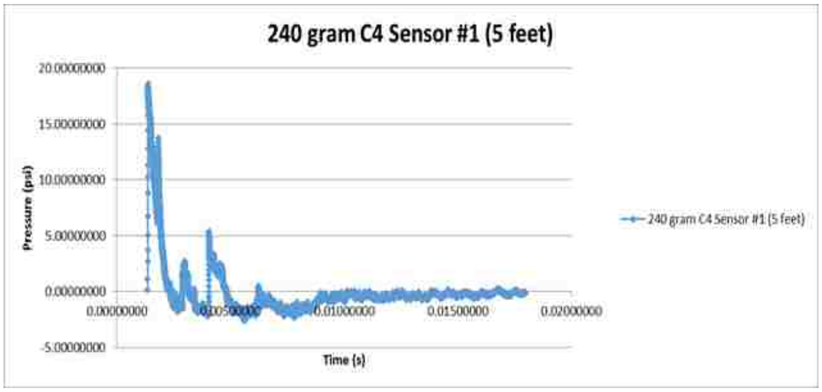


Figure B3.1: 240-gram C4 Charge Pressure versus Time Graph Sensor #1 (5 feet)

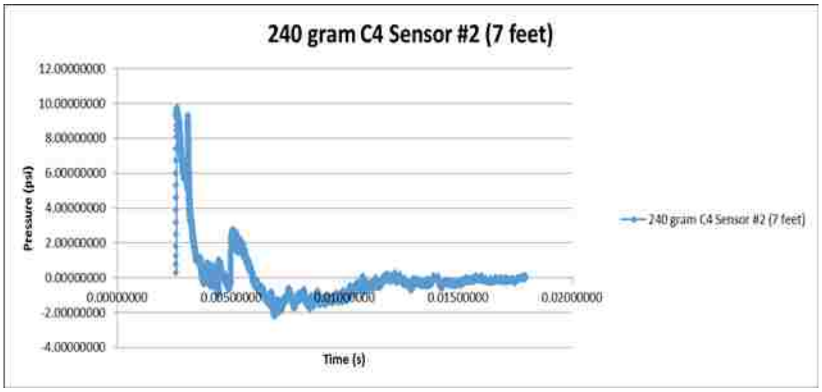


Figure B3.2: 240-gram C4 Charge Pressure versus Time Graph Sensor #3 (7 feet)

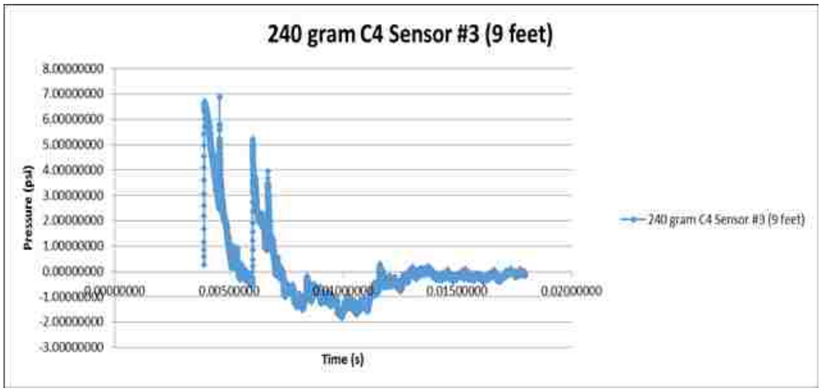


Figure B3.3: 240-gram C4 Charge Pressure versus Time Graph Sensor #3 (9 feet)

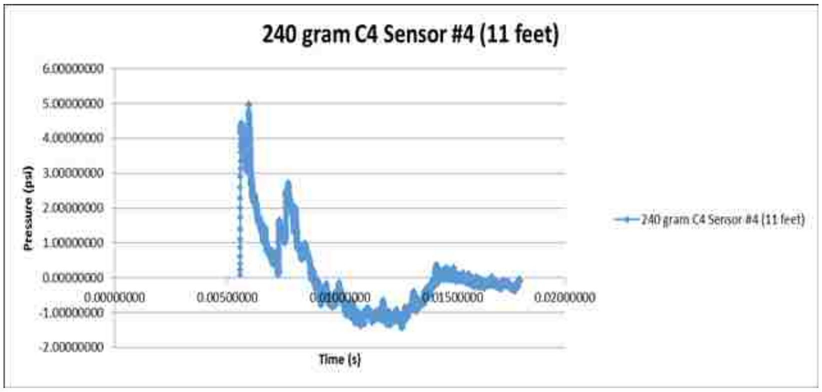


Figure B3.4: 240-gram C4 Charge Pressure versus Time Graph Sensor #4 (11 feet)

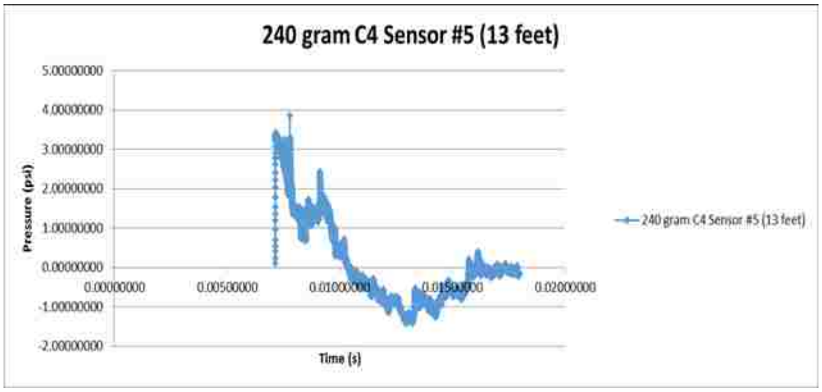


Figure B3.5: 240-gram C4 Charge Pressure versus Time Graph Sensor #5 (13 feet)

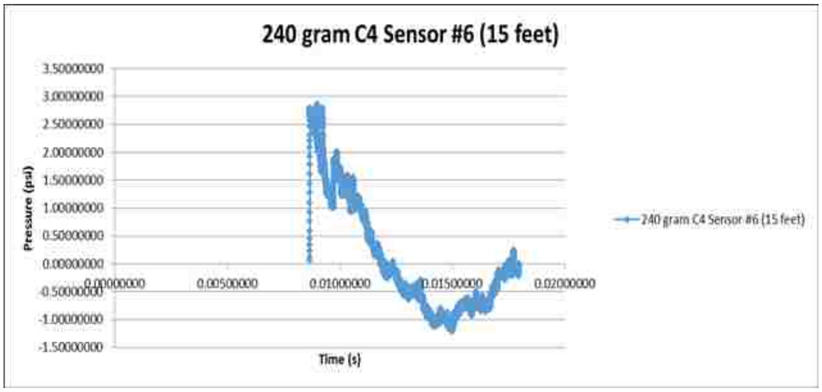


Figure B3.6: 240-gram C4 Charge Pressure versus Time Graph Sensor #6 (15 feet)

APPENDIX C.

PHOTOGRAPHS OF BARRIER BAG DAMAGE INCURRED DURING TESTING

The figures contained within Appendix C. are photographic exhibits of the barrier bag damage resulting from the open air and shock tunnel testing. Each is labeled with its testing charge weight, and bag location position and distance from the charge. Figures C1 through C1.6 contain images from the open-air testing, while Figures C2 through C2.2 contain images from the shock tunnel testing.

Figure C1: 60g C4 Test Bag Position 1 (5 ft)

Figure C1.1: 120g C4 Test Bag Position 2 (7 ft)

Figure C1.2: 120g C4 Test Bag Position 3 (9 ft)

Figure C1.3: 240g Shot - Bag Positions 1 and 2 (5 and 7 ft)

Figure C1.4: 240g C4 Test Bag Position 3 (9 ft)

Figure C1.5: 240g C4 Test Bag Position 4 (11 ft)

Figure C1.6: 240g C4 Test Bag Position 6 (15 ft)

Figure C2: 40g C4 Test Bag Distance 31 feet

Figure C2.1: 40g C4 Test Bag Distance 35 feet

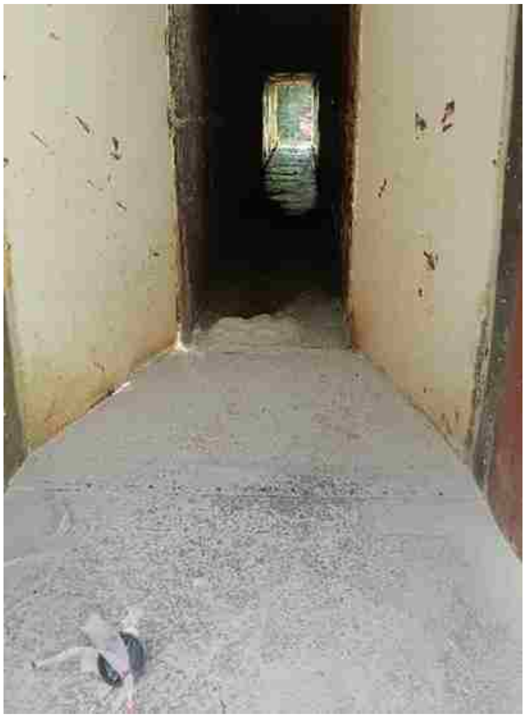


Figure C2.2: 40g C4 Test Bag Distance 39 feet

APPENDIX D.

MATERIALS AND EQUIPMENT UTILIZED IN SHOCK TUNNEL TESTING OF BARRIER BAGS

The contents of Appendix D include a listing of the equipment and materials required to complete the 40-gram C4 shock tunnel testing of the barrier bags at the Missouri S&T Experimental Mine Facility's Shock Testing Tunnel.

- PPE (Hard Hats, Safety Glasses, Hearing Protection)
- Digital Camera
- Remote Trigger Box and Interface Cable
- Data Acquisition System
- 6 Piezoelectric Pressure Transducers
- 6 Pressure Transducer Coax Cables
- 6 Pressure Transducer Stands
- 4 Skillpro Stone Dust Bags
- 2 Power Extension Cords
- Scorpion Initiation Box
- Blasting Cable Reel
- Trigger Cable Reel
- 1 Roll Wire – Charge Hanging
- Extra Electrical Wire for Cap Mounted Triggers
- 1 Roll Electrical Tape
- Tape Measure
- Table
- #8 Blasting Caps (electric) – Qty:4
- 40-gram Spherical C4 Charge – Qty:4

- 2 Barricades and Warning Signs
- GoPro Camera and Tripod
- Laptop Computer

APPENDIX E.

PRESSURE AND IMPULSE DATA FROM SHOCK TUNNEL TESTING

The contents of Appendix E include two tables containing the pressure and impulse data versus sensor location and charge distance of the shock tunnel pressure testing performed during this project.

Table E1: Shock Tunnel Pressure Testing Pressure Data

	[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table E2: Shock Tunnel Pressure Testing Impulse Data

	[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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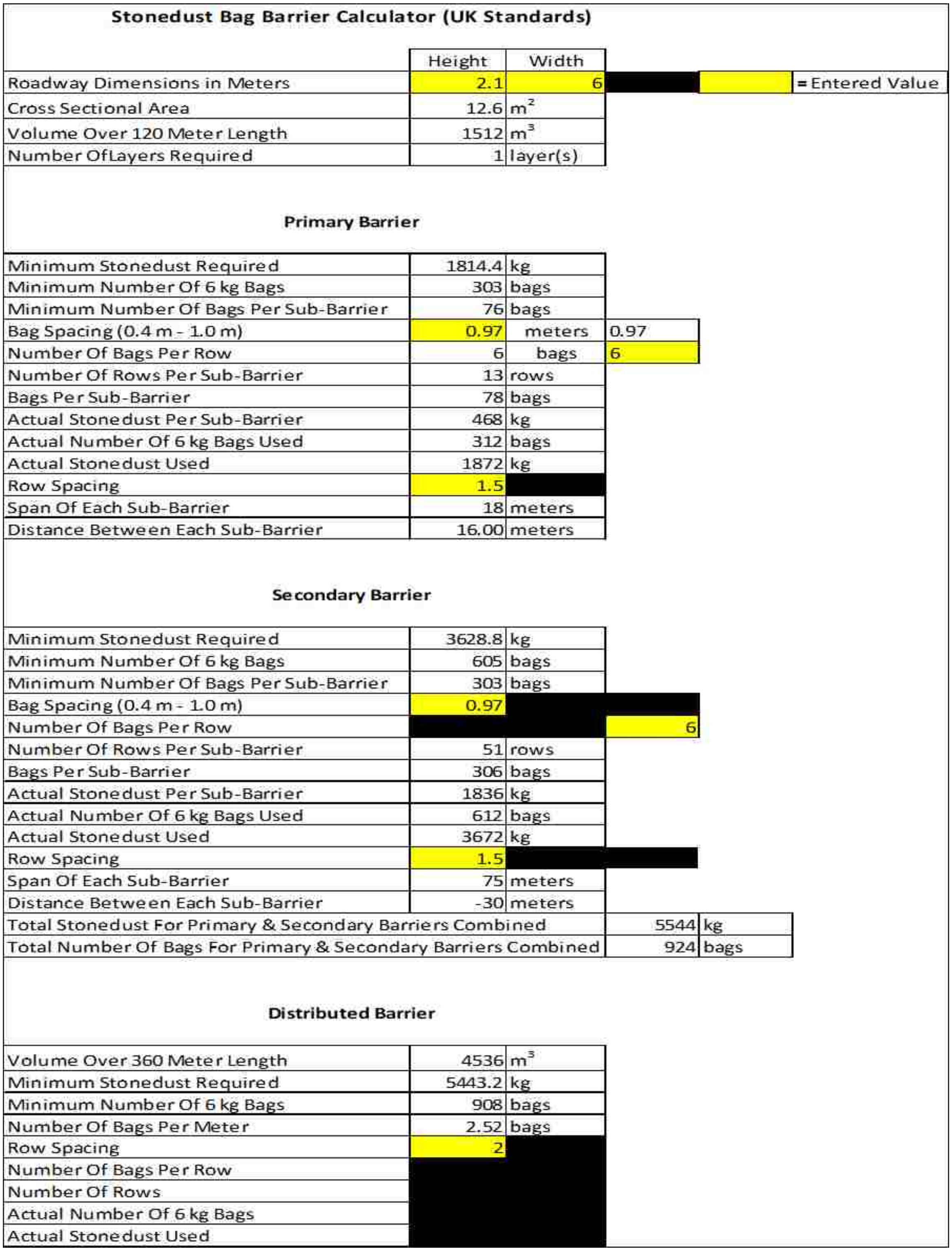
APPENDIX F.

BAG BARRIER SUPPLIES CALCULATOR SHEETS

A Bag Barrier supplies calculator spreadsheet was developed, based on the UK regulations, to quickly output the maximum number of bags, hooks, and stone dust amount required to install a bag barrier system in a given mine. Also, the number of rows of bags, and the number of bags per row for different barrier configurations was also output. This was done by inputting mine tunnel dimensions and bag spacing information. Included in this Appendix are copies of the completed calculator spreadsheet for both mine trial installations.



Stonedust Bag Barrier Calculator (UK Standards)

	Height	Width			
Roadway Dimensions in Meters	2.1	6		🟨	= Entered Value
Cross Sectional Area	12.6	m^2			
Volume Over 120 Meter Length	1512	m^3			
Number OfLayers Required	1	layer(s)			

Primary Barrier

Minimum Stonedust Required	1814.4	kg	
Minimum Number Of 6 kg Bags	303	bags	
Minimum Number Of Bags Per Sub-Barrier	76	bags	
Bag Spacing (0.4 m - 1.0 m)	0.97	meters	0.97
Number Of Bags Per Row	6	bags	6
Number Of Rows Per Sub-Barrier	13	rows	
Bags Per Sub-Barrier	78	bags	
Actual Stonedust Per Sub-Barrier	468	kg	
Actual Number Of 6 kg Bags Used	312	bags	
Actual Stonedust Used	1872	kg	
Row Spacing	1.5		
Span Of Each Sub-Barrier	18	meters	
Distance Between Each Sub-Barrier	16.00	meters	

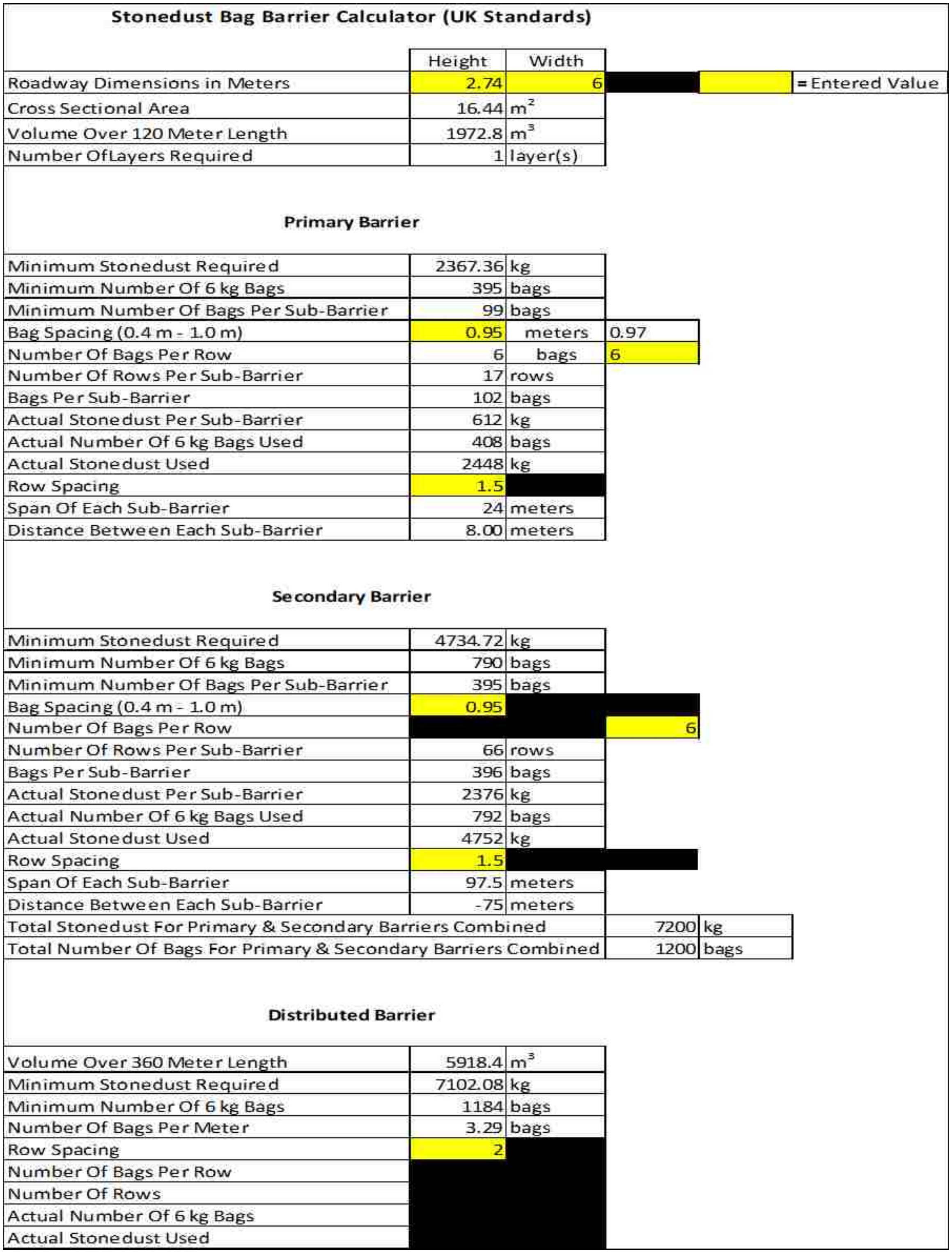
Secondary Barrier

Minimum Stonedust Required	3628.8	kg		
Minimum Number Of 6 kg Bags	605	bags		
Minimum Number Of Bags Per Sub-Barrier	303	bags		
Bag Spacing (0.4 m - 1.0 m)	0.97			
Number Of Bags Per Row			6	
Number Of Rows Per Sub-Barrier	51	rows		
Bags Per Sub-Barrier	306	bags		
Actual Stonedust Per Sub-Barrier	1836	kg		
Actual Number Of 6 kg Bags Used	612	bags		
Actual Stonedust Used	3672	kg		
Row Spacing	1.5			
Span Of Each Sub-Barrier	75	meters		
Distance Between Each Sub-Barrier	-30	meters		
Total Stonedust For Primary & Secondary Barriers Combined			5544	kg
Total Number Of Bags For Primary & Secondary Barriers Combined			924	bags

Distributed Barrier

Volume Over 360 Meter Length	4536	m^3
Minimum Stonedust Required	5443.2	kg
Minimum Number Of 6 kg Bags	908	bags
Number Of Bags Per Meter	2.52	bags
Row Spacing	2	
Number Of Bags Per Row		
Number Of Rows		
Actual Number Of 6 kg Bags		
Actual Stonedust Used		

Figure F1: Bag Barrier Calculator Sheet for Mine #1



Stonedust Bag Barrier Calculator (UK Standards)

	Height	Width			
Roadway Dimensions in Meters	2.74	6		🟨	= Entered Value
Cross Sectional Area	16.44	m^2			
Volume Over 120 Meter Length	1972.8	m^3			
Number OfLayers Required	1	layer(s)			

Primary Barrier

Minimum Stonedust Required	2367.36	kg	
Minimum Number Of 6 kg Bags	395	bags	
Minimum Number Of Bags Per Sub-Barrier	99	bags	
Bag Spacing (0.4 m - 1.0 m)	0.95	meters	0.97
Number Of Bags Per Row	6	bags	6
Number Of Rows Per Sub-Barrier	17	rows	
Bags Per Sub-Barrier	102	bags	
Actual Stonedust Per Sub-Barrier	612	kg	
Actual Number Of 6 kg Bags Used	408	bags	
Actual Stonedust Used	2448	kg	
Row Spacing	1.5		
Span Of Each Sub-Barrier	24	meters	
Distance Between Each Sub-Barrier	8.00	meters	

Secondary Barrier

Minimum Stonedust Required	4734.72	kg		
Minimum Number Of 6 kg Bags	790	bags		
Minimum Number Of Bags Per Sub-Barrier	395	bags		
Bag Spacing (0.4 m - 1.0 m)	0.95			
Number Of Bags Per Row			6	
Number Of Rows Per Sub-Barrier	66	rows		
Bags Per Sub-Barrier	396	bags		
Actual Stonedust Per Sub-Barrier	2376	kg		
Actual Number Of 6 kg Bags Used	792	bags		
Actual Stonedust Used	4752	kg		
Row Spacing	1.5			
Span Of Each Sub-Barrier	97.5	meters		
Distance Between Each Sub-Barrier	-75	meters		
Total Stonedust For Primary & Secondary Barriers Combined			7200	kg
Total Number Of Bags For Primary & Secondary Barriers Combined			1200	bags

Distributed Barrier

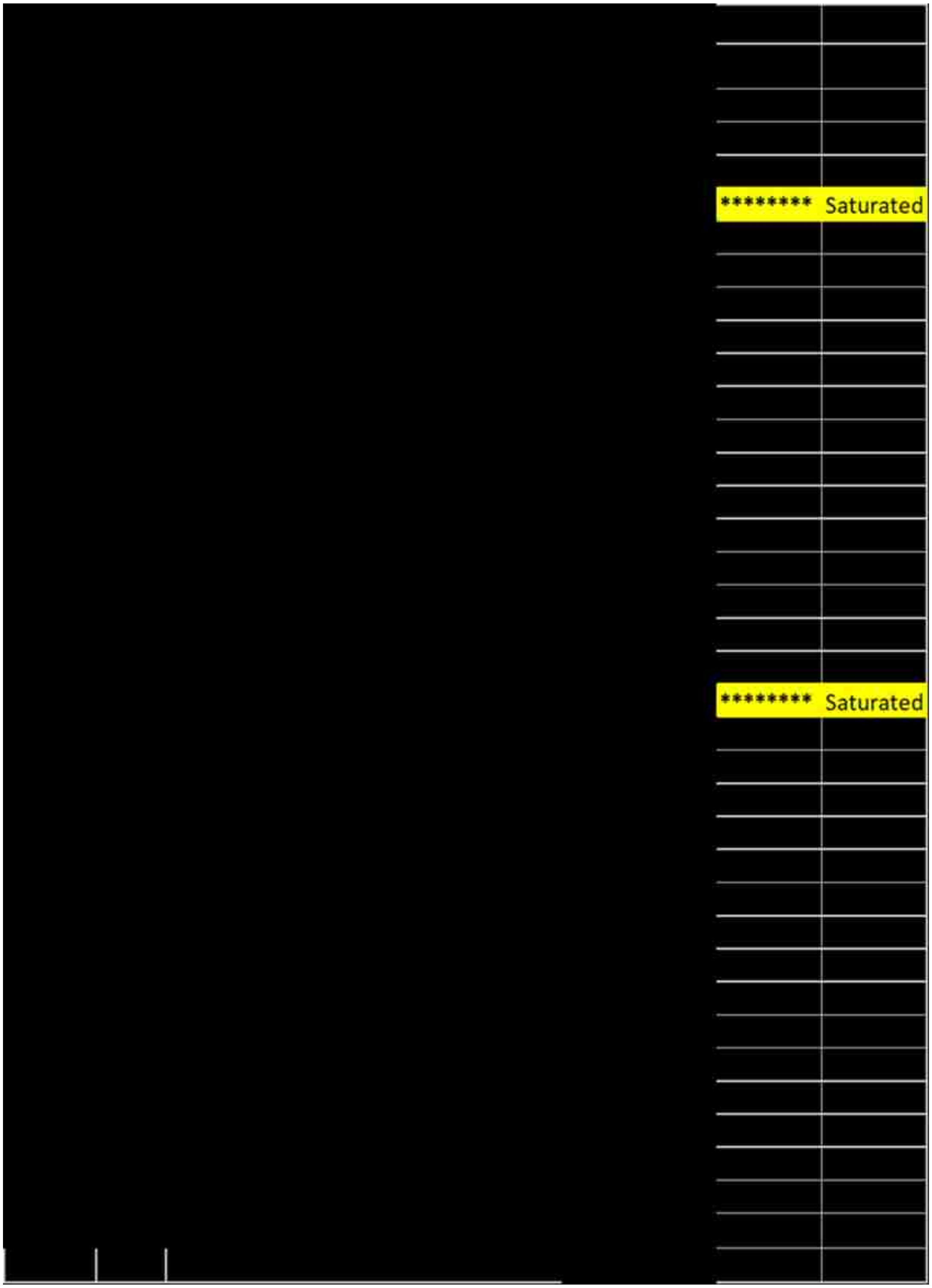
Volume Over 360 Meter Length	5918.4	m^3
Minimum Stonedust Required	7102.08	kg
Minimum Number Of 6 kg Bags	1184	bags
Number Of Bags Per Meter	3.29	bags
Row Spacing	2	
Number Of Bags Per Row		
Number Of Rows		
Actual Number Of 6 kg Bags		
Actual Stonedust Used		

Figure F2: Bag Barrier Calculator Sheet for Mine #2

APPENDIX G.

ENDING LIMESTONE DUST MOISTURE CONTENT ANALYSIS OF ALL 35 BAGS

An investigation into the barrier bags' ability to prevent moisture contamination of the enclosed stone dust was undertaken. Thirty-five bags were filled and hung at the Missouri University of Science and Technology's Experimental Mine for a full year. The ending results of the moisture content analysis of all 35 bags is included in this appendix.



[redacted]

******** Saturated

******** Saturated

Figure G1: Ending Limestone Dust Moisture Content Analysis of All 35 Bags

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