# Surface Coal Mine Blasting Optimization and Mitigation of Environmental Impacts: Mine to Fill

**Catherine E. Johnson**
University of Kentucky, Lexington, Kentucky

**Braden T. Lusk**
University of Kentucky, Lexington, Kentucky

**Joshua M. Hoffman**
University of Kentucky, Lexington, Kentucky

**John T. Rathbun**
University of Kentucky, Lexington, Kentucky

## ABSTRACT

Environmental impacts from blasting are traditionally related to the control of vibration, airblast levels and flyrock near mine operations. None or very little work either experimental or theoretical has been performed regarding environmental impacts from blasting with reference to surface water and air quality. Other aspects could be considered, resulting from the fragmentation of the blasted material and its final use as fill material. This paper discusses the optimization of mine blasting activity in surface coal mines based on the premise of mitigating environmental impacts different from those traditionally studied. This mine to fill analysis is conceptualized through applying classical fragmentation analysis.

A conceptual downstream cost analysis of the blasting activity is introduced to evaluate the impacts of the environmental improvements in the blast in the final mining cost. Fragmentation is a key element in the analysis due to the nature of the use of overburden material throughout the mine processes for reclamation and fill purposes. Environmental impacts of the earth fills in coal mines can be directly related to the properties of material used for the earth fills. The final result of this study is a concept for specifying material for specific use, placement and handling in surface coal mines. A matrix of specifications is introduced and will allow for future optimization of overburden handling with consideration of blasting parameters once finalized specifications are determined.

## INTRODUCTION

In the past environmental effects of blasting have predominantly been evaluated by measuring its direct effects. The effects most easily measured traditionally were ground vibrations and air overpressures. Blast optimization therefore sought to minimize ground vibrations and air overpressures while maintaining needed fragmentation and production rates at an economically feasible level. An optimized blast design is one that will break or move rock to the required fragment size for secondary equipment, to efficiently handle it, while minimizing secondary components such as cost and ground vibration effects. To that end, the optimization of blasting is not achieved in the same way at every site.

In addition to these optimization regimes one is proposed that considers indirect environmental effects of blasting. These environmental effects include conductivity, selenium content, Total Suspended Solids (TSS), Total Dissolved Solids (TDS), reforestation, vegetation growth, wildlife and wildlife habitat reintroduction in water runoff from fills created with blasted overburden material. Just as designs to optimize fragmentation and vibration can run counter to one another so can optimization for the different environmental effects. The materials created from blasting events need to be evaluated to determine their short and long term environmental impacts of the fill areas into which the blasted materials are placed. Means of reducing targeted impacts can be achieved through redesigning blasts to produce rock materials with particle sizes, densities, distributions, and compositions that minimize negative environmental impacts. Optimized fill material will change throughout the construction of the fill and this temporal component must be considered as well.

These material particle sizes, densities, distributions, and compositions vary depending on the different environmental impacts that are to be mitigated and the materials in question. Creating these different material specifications can be aided through blasting practices. This process potentially means moving away from the most economical method of removing overburden to one that weighs environmental impacts. This is the cost/benefit associated with the optimization of blasting to minimize the impacts on a given environmental concern. Mining operations must be optimized through their entire operational cycles. There are real costs associated with environmental considerations such as lengthy permitting process, regulatory fines, reclamation, and high capital water treatment facilities. Increased costs associated with processes early on in the cycle, such as blasting, could offset long term remediation costs.

Optimizing blasts to produce materials with required sizes and distributions can be aided by mathematical models which predict particle size and distribution. These models have typically been utilized to design blasts which produce fragment sizes that are best for secondary crushing or handling. It is shown in later sections that these models can be applied to typical blasts from the Appalachian Region. Provided the final product specifications of the rock material are known, blasts can be designed using this optimization process.

## TRADITIONAL ENVIRONMENTAL IMPACTS OF BLASTING

Traditionally environmental effects of blasting have been limited to areas of vibration, air overpressure, and flyrock. These effects have been targeted for research and improvement due to the immediacy of their effects, the regulations which govern their limits, and the relative ease by which they are measured. Early work in these areas was conducted by the United States Bureau of Mines. These efforts led to the development of field feasible methods of measuring ground vibrations (Lee, Thoenen and Windes 1936) and air overpressure (Ireland 1942). Over time better methods and tools for measuring ground vibrations and air overpressure were researched (Blair, 1954, Stachura 1981). Eventually, as reliable measurements were made possible, attention was turned to monitor the effects that measurable vibrations had on nearby structures (Edwards 1960, Duvall 1962, Northwood 1963, Nicholls 1971, Medearis 1977, Siskind 1980a, Siskind 1980b, Clark 1983, Stagg 1984, Siskind 1985, Shaw 1989, Siskind 1993, Siskind 2000, Adhikari 2005). Much of this work aided in the promulgation of legislation which regulated mine blasting and defined ground vibration and air overpressure limits. Legislation such as Surface Mining Control and Reclamation Act of 1977 created a regulatory environment that encouraged improvement.

While vibration and damage monitoring work continues today, it has been joined by the companion focus of altering aspects of a blast with the intention of controlling ground vibrations and air overpressures. This research led to theories and methods to reduce ground vibration and air overpressure (Duval 1963, Siskind 1985, Stachura 1986, Kopp 1986, Siskind 1989). Although much of the theory for ground vibration waveform tailoring was developed in the 1980s it has been revisited in recent years due to the introduction of the economically viable electronic detonator.

Flyrock incidents have occurred for as long as there has been blasting. Most research looks into causes and offers up best practices for the prevention of flyrock (Ash 1975, Watson and Roth 1978, Fletcher and D'Andrea 1986, Bajpayee 2003, Bajpayee 2004, Little 2007). This was made imperative as regulations defined flyrock and contained provisions for flyrock control and avoidance (Dick 1979).

## SECONDARY ENVIRONMENTAL IMPACTS OF BLASTING

Contemporary environmental concerns that have come under more scrutiny are those of long term environmental impacts. These are focused around water quality, air quality, and resulting downstream habitat effects. Although these are often a result of mining practices as a whole, solutions could be found in the manner in which blasting occurs.

Much of the work investigating gas emissions from blasting has taken place on the laboratory scale. These experiments emulated differential conditions in the field such as explosive contamination and confinement to study their effects on gaseous product production (Chaiken, Cook, and Ruhe 1974, Persson and Persson 1980, Mainiero 1997). Field work on the subject has proven less than conclusive given the physical challenges associated with monitoring gas emissions from entire blasts (Schettler and Brashear 1996, Onederra et al. 2012).

Lashgari et al. (2012) discuss work related to NOx emissions from both blasting and diesel equipment at a specific mine site. Highest NOx emissions come from Haul trucks (44.69%), clearly a truck that is not at full capacity due to a poor distribution of particle sizes will increase the number of trucks and reduce the air quality. Furthermore, blasting is calculated to contribute to the next highest level of NOx emissions at a mine site, increasing explosive quantity or strength to produce different particle sizes will also increase the level of NOx produced at the mine site. Shovel productivity in terms of swings per hour could be reduced if the required size distribution is found to be too great for the bucket size, increasing both cost and air quality. A balance between all environmental effects needs to be established; simply improving one area can have a negative effect on another.

This paper focuses on the potential environmental impacts from materials that have been blasted based on their fragmentation sizing, distribution, and placement. The fills in which the blasted materials are placed are the areas from which environmental concerns arise. These environmental effects include conductivity, selenium content, TSS, TDS present in runoff waters, as well as reforestation, vegetation growth, wildlife and wildlife habitat reintroduction. While these effects will vary with different strata and rock materials (Williams 1994) they will also vary based on the fragment size, and distribution. These latter two qualities can be altered through different blasting practices. Work can be done to develop better ways to construct fills using material with properties that has been historically produced from surface coal mines. This however takes blasting to be a "black box" from which the same material will always be produced. Instead blasting must be considered in this work as well for its ability to produce materials better suited for fill construction.

## COMPREHENSIVE EFFECTS OF BLASTING PRACTICES

The cycle associated with mining and reclamation is: Drill, Blast, Dig, Move, Place, Wait, Monitor, React. This overall cyclical operation must be optimized to allow for continued operation and adaptation during increased regulatory scrutiny on the back end of the cycle. These alterations must be evaluated economically as well as environmentally. The effects changes in blasting have on overall operational costs cover everything from drilling and blasting to final placement and reclamation of the material. The concept of mine to mill is not new to the mining industries that process blasted materials (Kanchibotla and Valery 2010). Considering an overall process for blasted overburden is very similar to mine to mill and could be termed "mine to fill." What is proposed in this paper takes into account environmental impacts of these alterations and the associated economics with remediating those impacts. Fragmentation is the first step in this cycle and therefore the first place to make alterations with the intention of improving downstream effects.

Hissem (2013) advises a Lean Six Sigma cost and waste elimination model for an aggregate quarry that demonstrates a relationship between the degree of rock fragmentation and cost per ton. Poor fragmentation from blasting will simply increase costs through hauling, crushing or grinding. There is an optimum that can be found to satisfy all aspects of the quarry cycle for both cost and productivity with just a few changes to personnel attitude and pit design. Drilling is the start of the cost structure; it directly affects the blast, which in turn affects the cost. In a similar way to how the initial blast can directly affect the final cost to the mine, it also has a direct effect to the final environmental issues of the mine. Rather than the pit and plant being seen as separate entities, they should be considered one smooth transition with each affecting the next step, meaning improvements from the start will affect the end result. A similar model and idea can be applied to the ‘environmental cost.’

Optimized mine fill for environmental purposes should comprise of a series of rock filters at the base before the main bulk fill is placed. This practice is well established and allows for reduced environmental effects from water runoff at the fill sites. Filters are best formed from medium grain grey sandstone, generally found at surface coal sites (Warner, personal email communication). These materials are particularly robust and allow for less outfall issues such as TDS, conductivity, and Selenium content. Other material found in Appalachian surface coal mines would be used in the main fill material above the filter and drains thus isolating them (Figure 1).

Through a series of blast designs which target the size ranges for the rock drain, primary, secondary and tertiary filters, it is possible to produce enough material to successfully create the proposed filter design. Only the initial blasts would have to be specifically designed to produce the material desired for the filters, not every blast at the mine site. Changes in blast design have been shown to allow for shifting of the distribution curve for fragmentation. These changes would suggest that blast design could be altered to create more material of a desired size fraction. Considerable adjustment to the blast design may be necessary to achieve such drastically different materials. In the initial stages of fill construction, considerable effort and attention would be required in the blasting phase to achieve the "specified" material. Some additional processing may be necessary, but could be as simple as a grizzly to allow for fine material to pass and not be utilized for drain and filter construction. If a sufficient filter is created for the fill without the use of mechanical separation, solely adapted blast design, it is possible to produce a cost effective, environmentally improved reclaimed mine site.

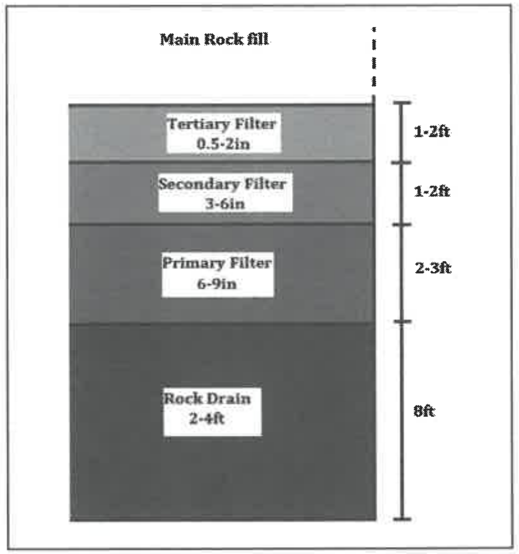

**Figure 1. Proposed filter dimensions for fill (Warner, personal email communication)**

## INTRODUCTION TO FRAGMENTATION MODELLING AND ASSESSMENT

Blasting is used throughout the surface coal mining industry for effective overburden removal. Ideal fragmentation sizes have long been created through adaptations to blast design in order to optimize mine productivity and for commercial

**Table 1. Rock factor parameters (Lilly, 1983)**

| | | |
|---|---|---|
| Rock Mass Description (RMD) | Powdery/Friable | 10 |
| | Blocky | 20 |
| | Totally Massive | 50 |
| Joint Plane Spacing (JPS) | Close (<0.1m) | 10 |
| | Intermediate (0.1 to 1m) | 20 |
| | Wise (>0.1m) | 50 |
| Joint Plane Orientation (JPO) | Horizontal | 10 |
| | Dip Out of Face | 20 |
| | Strike Normal to Face | 30 |
| | Dip into Face | 40 |
| Specific Gravity Influence (SGI) | SG in tonnes/$m^3$ | 25(SG-50) |
| Hardness Factor (HF) | Elastic Modulus(GPa)/3 | 1–10 |

use. Fragmentation has a central influence over mine productivity and cost; MacKenzie (1966) described optimum fragmentation to be "that blasting practice which gives the degree of fragmentation necessary to obtain the lowest unit cost of the combined operations of drilling, loading, hauling and crushing." Overburden is effectively mine waste and has been removed in the most cost effective manner and is often used as fill material in mine reclamation. Typically, blast optimization for overburden has been guided towards optimizing loader and haul truck productivity. Loader productivity is a direct function of the range of rock sizes a loader bucket has to juggle in each filling; both large rocks too big for a loader bucket, and small rocks that simply fall out of the bucket while in a swing motion will impede productivity, consequently increasing the number of bucket loads per blast and therefore costs. Having a medium and uniform size range may consequently increase productivity and reduce overall operation costs. Fill material is usually taken from the muck pile to an overburden waste dump to be used in a fill at a later date for rehabilitation purposes or directly to a fill. Typically no grading or sorting of particle size is carried out in these dumps, even though for stability and water contamination purposes, separate layers of sized material are beneficial. Fine particles are unwanted in fills due to their large surface area and susceptibility to the transport of contaminants such as selenium, TDS or conductivity.

A number of models have been established to predict size distributions from specific blast designs. Predictions are made either through empirical or mechanistic modeling. Empirical modeling assumes finer fragmentation from higher energy input whilst mechanistic modeling tracks the physics of detonation and the energy transfer for specific blast layouts. Quite clearly the mechanistic model requires more data so is more difficult to apply on a day to day basis, therefore, empirical models are most often used for the prediction of fragmentation size. One of the first empirical fragmentation models with respect to blasting is the Kuz-Ram model. The model was established by Cunningham in 1983 as an easy method of estimating fragmentation based on geometric parameters of the drilling and blast design. A mean size is calculated using blast parameters (Kuznetsov 1973) and the fragmentation spread is based on an adapted version of the Rosin-Rammler equation. Four equations are required for the model:

Adapted Kuznetsov equation:

$$x_m = AK^{-0.8} Q^{\frac{1}{6}} \left(\frac{115}{RWS}\right)^{\frac{19}{20}} \qquad (1)$$

where $x_m$ = mean particle size (cm); A = rock factor; K = powder factor (kg/$m^3$); Q = mass of explosive in the hole (kg); RWS = weight strength relative to ANFO, 115 being the RWS for TNT.

Rock Factor, A:

$$A = 0.06(RMD + JPS + JPO + SGI + HF) \qquad (2)$$

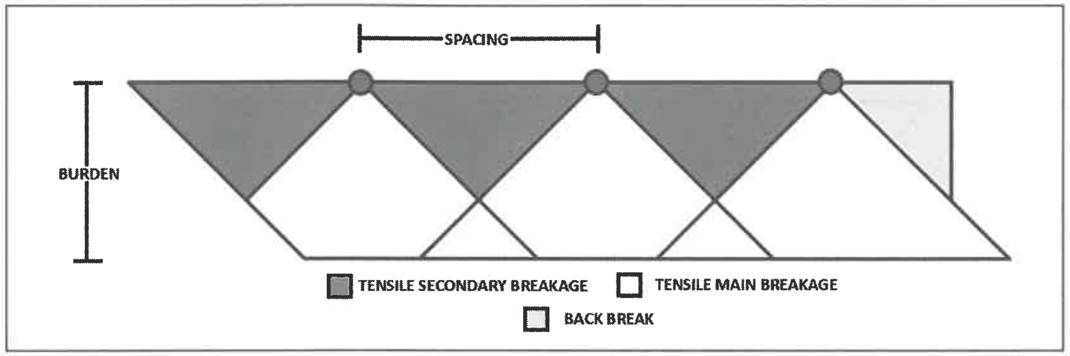

**Figure 2. Breakage mechanisms identified by Rollins (1990)**

Adapted Rosin-Rammler equation:

$$R_x = \exp\left[-0.693\left(\frac{x}{x_m}\right)^n\right] \qquad (3)$$

where $R_x$ = mass fraction remained on screen opening $x$; n = uniformity index, between 0.7 and 2.

Uniformity equation:

$$n = \left(2.2 - \frac{14B}{d}\right)\sqrt{\left(\frac{1 + S/B}{2}\right)}\left(1 - \frac{W}{B}\right) \left(abs\left(\frac{BCL - CCL}{L}\right) + 0.1\right)^{0.1} \frac{L}{H} \qquad (4)$$

where B = burden (m); S = spacing (m); d = hole diameter (mm); W = standard deviation of drilling precision (m); L = charge length (m); BCL = bottom charge length (m); CCL = column charge length (m); H = bench height (m) (Cunningham 1983).

The model is simple to use due to the ease of access to data for all parameters involved and does not involve a lengthy image analysis process. Despite this, it has been scrutinized for its lack of inclusion of all parameters involved with rock fragmentation and an underestimation of the prediction of fines (fragments less than 50 mm). Lownds (1983) identified that the uniformity parameter is not influenced by mechanical properties of the rock or characteristics of the explosive. Fragmentation prediction by Cunningham (1983) assumes that a single distribution of pre-existing discontinuities is present within the rock mass and that tensile failure is the main mechanism of failure. A tensile stress field is created around each blasthole extending radial cracks as it initiates. The interaction between radial cracks from different blastholes and the free face create rock fragments.

Rollins (1990) acknowledged that explosive properties and mechanical rock properties are not fully considered within the original Kuz-Ram model, only the drilling pattern and general rock mass factors based on an original model by Lilly (1986) (Table 1). He developed a separate model that takes into account different tensile breakage mechanisms that occur due to explosive interaction with the rock. Breakage mechanisms identified include the main breakage area, secondary breakage and a back break area, shown in Figure 2. The boundary of the main breakage area is found from the magnitudes of the strain from the tensile stress waves and the tensile strength of the rock. The secondary breakage area is determined by tensile stress wave reflections at discontinuities and interactions from adjacent boreholes. The back break area is that beyond the main breakage area where reflected tensile waves no longer break the rock. A rock volume for the main breakage area is calculated for each hole and individual mean fragmentation sizes and a fragmentation distribution for each borehole are calculated using Equations 1 and 3, respectively; an average is taken of all boreholes calculated. In order to calculate the breaking area more in depth analysis of the specific explosive used and individual rock parameters around each blast hole are required. Comparing this model to field data showed excellent results for the fine

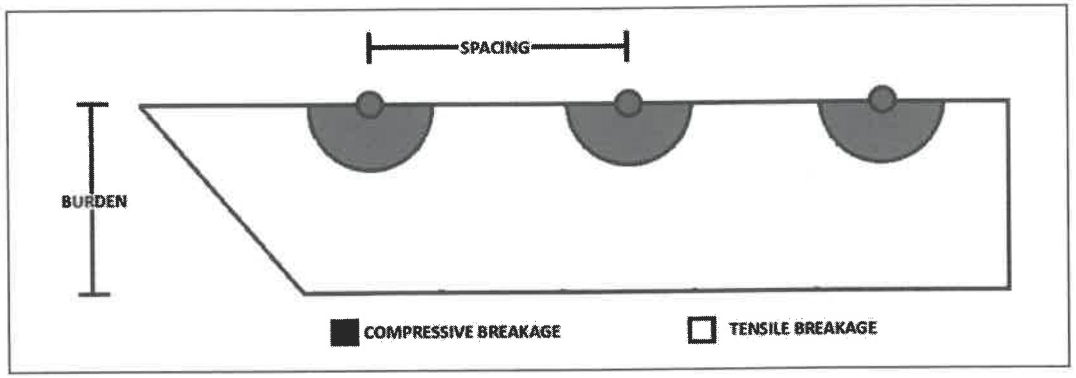

**Figure 3. Compressive and tensile stress rock breakage**

end of the spectrum, far more accurate than using the total volume of rock as in the original model by Cunningham (1983), however, the model is based on a small scale, ideal, test (Rollins 1990).

The Rollins model still only takes into account tensile breakage; in reality, there are two very different mechanisms that cause rock fragmentation, both tensile failure, and compressive shear failure (Figure 3). Compressive shear failure occurs close to the blasthole and creates much smaller particles. In hard rock blasting, fragmentation models such as the Kuz-Ram give a good result since the effects of compressive shear failure are minimal. Softer rocks, however, have a significant amount of compressive shear failure and therefore this parameter should be taken into account in the prediction of fragmentation size, this also explains the underestimation of fines in the original Kuz-Ram model. Djordjevic (1999) developed a two component model for cases where fragmentation of the given rock volume occurs due to two different mechanisms. The $d_{50}$ size calculated from equation 1 is used for the coarse distribution of sizes. The mean size of fines, typically under 50 mm, are considered separately. The model gives a better estimation to the full spectrum of fragmentation sizes. The two separate $d_{50}$ sizes are input into a modified version of Equation 3 to give:

$$R_x = 1 - (1 - F_c) \cdot \exp\left[-0.693\left(\tfrac{x}{a}\right)^b\right] - F_c \cdot \exp\left[-0.693\left(\tfrac{x}{c}\right)^d\right] \qquad (5)$$

where a and c = mean fragment sizes in the tensile and compressive failure regions, respectively; b and d = uniformity coefficients in the tensile and compressive failure regions, respectively and $F_c$ = the total mass of rock failed by shear compressive strength, given by:

$$F_c = \frac{M_o}{M} \qquad (6)$$

where $M_o$ = mass of rock failed in compression and M = total mass of rock per blast hole.

Kanchibotla et al. (1999) hypothesize that fines are produced by the crushing action of the rock adjacent to the blast holes. A cylindrical volume, similar to that shown in Figure 3 as compressive breakage, is determined by calculating the point at which radial stress around the blast hole exceeds the dynamic compressive strength of the rock. The distribution of the coarse fraction (>1 mm) and the fine fraction of the rock are considered separately. Predictions using this model have been used on several mine sites, the resulting size distributions on the fines zone are far superior to those from the original Kuz-Ram model (Kanchibotla et al. 1999). Ouchterlony (2004) incorporates a third parameter to account for the upper limit cut-off of block sizes from the original model giving correlation coefficients with sieved data of at least 0.997.

## DISCUSSION

The Cunningham model has typically been popular for fragmentation distribution prediction,

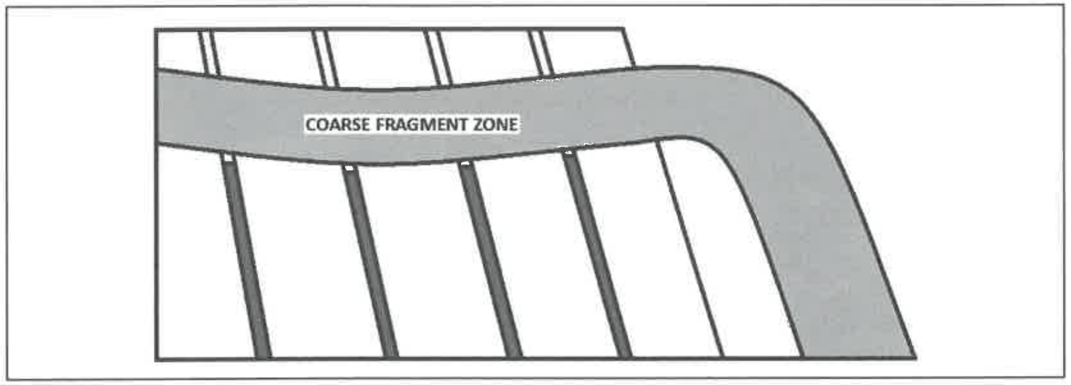

**Figure 4. Coarse fragmentation zone from a blast (Kanchibotla et al. 1999)**

despite its known underestimation of fines (Kojovic 1995, Comeau 1996, Rollins 1990, Djordjevic 1999, Kanchibotla et al. 1999). This is because blasting engineers are typically interested in the +250mm size due to its affects in the loading and hauling operations, a crucial part of the overall mine cost. Accurate estimation of fines developed by the Djordjevic (1999), Kanchibotla et al. (1999) and Ouchterlony (2004) models are only necessary in operations where proportion of fines affects the price of the final product, such as iron ore, so the addition of even more parameters to an already extensive, predictive model is not often required. Nevertheless, fines could be a big factor in fill design since they will inevitably transport more waterborne contaminants. Therefore knowing the exact proportions of fines and their specific size could be crucial in mitigating these environmental effects.

Fragmentation distribution can be analyzed through photographic image analysis. A number of computer models have been developed including, but not limited to, GoldSize, (Kleine 1997) BLASTFRAG (Exedaktylos 1989) and WipFrag. Kanchibotla et al. (1999), discuss the systematic bias involved with image analysis due to the coarse fragmentation zone on the surface of the muck pile caused by the stemming zone where no explosive charge is present (Figure 4). Fragmentation in this zone is due to gas heave from the underlying explosive charge and secondary breakage through crushing and grinding during movement. To avoid sampling bias, images need to be taken at regular intervals throughout the digging process, possibly hindering the shovel and truck productivity. An image based software system needs to be able to distinguish between different particles, usually by identifying particle boundary pixels in a grey level scale. It is easy to confuse shadows with particle separation and the fine portion of the scale is near impossible to predict. Due to this, pre-processing work is often required to outline separate rock particles and identify areas of fines. Fines are not fully taken into account through image analysis; first, they are not always present on the surface due to settling, wind or rain, and secondly, individual fragments are too small to segregate due to image resolution limitations. Since fines are not often of high interest when looking at fragmentation distribution, they are often eliminated from the final size distribution in image analysis, but this is the specific users' choice.

When looking at Figure 4 and the consideration for the coarse fragmentation limitation for image analysis, it is apparent that the coarse fragmentation zone is not taken into account for the Kuz-Ram model. It has been discussed that the column charge (red in Figure 4) causes two types of failure, compressive and tensile, where the tensile fraction is considered in the original model. Attempts have been made to include the fines fraction into the model through two and three component models by Djordjevic (1999) and Ouchterlony (2004), respectively. However, no consideration for the upper end of the size

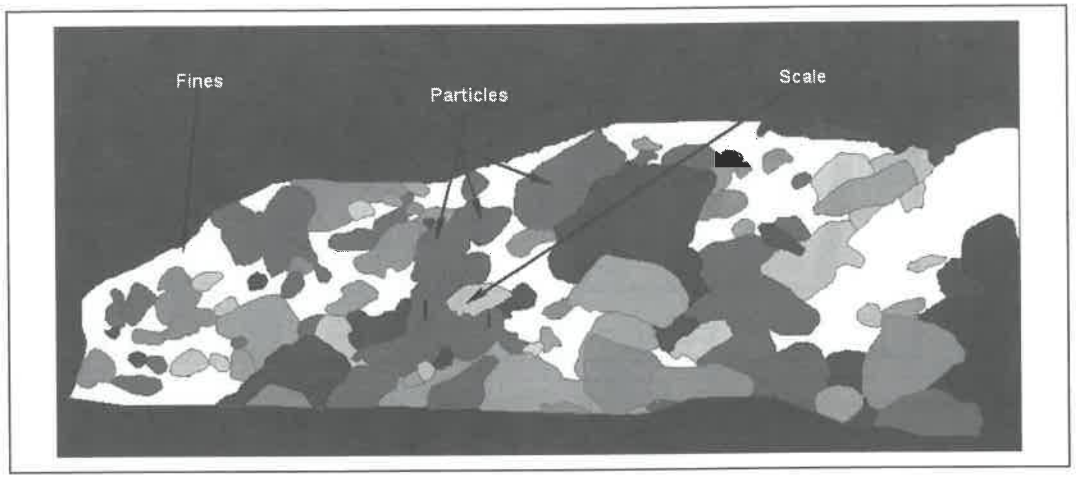

**Figure 5. Digital pre-processing work (Lee and Lusk 2012)**

distribution has been considered. When looking at blast optimization specifically for fill material, both extents of the scale are important and need to be considered within the models used.

A lot of research has been carried out on blast fragmentation to optimize overall mine costs, yet with increased legislation with respect to air and water quality in recent years more needs to be known with respect to the costs associated with optimizing size for mitigating these environmental effects. A comparison of ANFO versus 100% emulsion performance with equal drilling and blasting costs was carried out by Lee and Lusk (2012). Photographic fragmentation analysis, quantitative dig rates from time studies and qualitative rates about the digability of the blast from video recordings were utilized to evaluate the performance of the blast. Keeping the drill and blast cost per bank cubic yard the same for the two blasts ($0.46) produced a cost per hole of $170.76 for ANFO and $233.23 for emulsion. Results from the time study showed that the emulsion shot had a slightly lower average bucket time than the ANFO shot, of 31.98 seconds compared to 32.64 seconds. It was concluded that this was an insignificant time difference in terms of productivity and cost, but a lower standard deviation showed more consistency in digging. Digital photographs were taken of the muck pile throughout the shovel excavation to get a representative sample of the whole pile, two lasers were used for scale. WipFrag was used to analyze the fragmentation distribution after pre-processing was carried out to represent the rock particles. Fines, shown in white (Figure 5) were not taken into consideration in the WipFrag analysis.

A comparison of the average size distribution for the ANFO and emulsion shots is shown in Figure 6. The emulsion shot results in a smaller mean particle size than ANFO, which will become important in calculating costs for the full mine cycle and bucket load efficiency. The ANFO shot contained more blast holes for the same volume compared to the emulsion shot, 206 to 158, respectively. The higher amount of fines for ANFO, 45% passing 0.1in compared to 23% for emulsion can be attributed to the facts that there is a higher prevalence of holes in the ANFO shot and that fines are produced around each blast hole due to compressive stress.

Costs for the full mine cycle are required to gauge an idea of how varying the fragmentation size distribution of a blast muck pile will affect the overall mining costs. Ozdemir et al. (2007) developed an equation to estimate the bucket loading time ($T_L$) based on a CAT 330C LME:

$$T_L = 0.0103 * P_{50} + 3.60 \tag{7}$$

The lower mean particle size for emulsion of 9 inches compared to 11 inches for ANFO outputs a difference of 0.53 seconds in loading times and 49 buckets per hour, consequently increasing productivity; probably due to the increased powder factor for the emulsion shot (Lee and Lusk, 2012). The lower mean particle size will decrease cost with respect to bucket loading times, but the smaller particle size yields greater surface area for the transport of contaminants in water, such as TDS will be increased. There is clearly a balance between operational cost and the mitigation of environmental effects that has to be established. Calculating the final cost from mine to fill is possible through time studies and simple calculations.

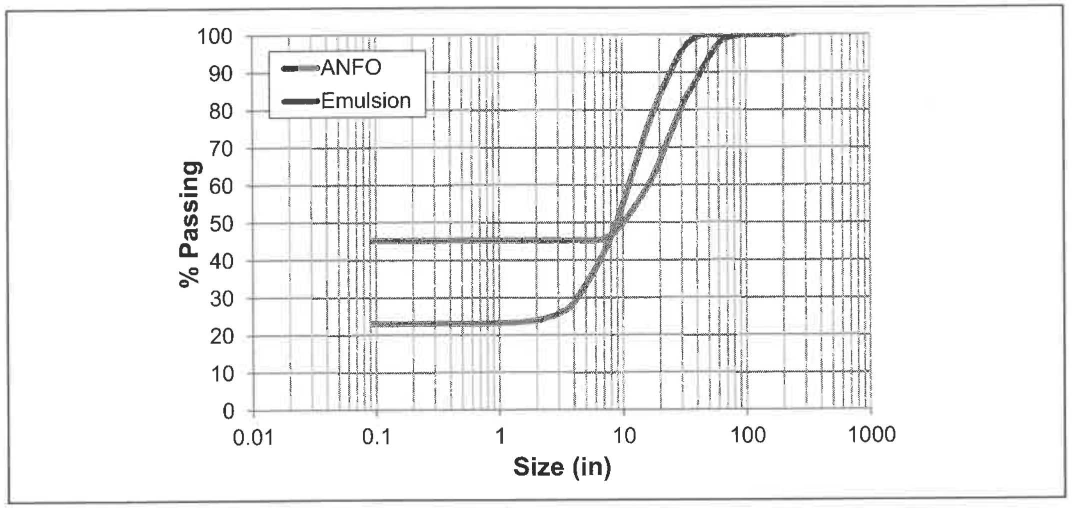

**Figure 6. Particle size distribution comparison ANFO–Emulsion (Lee and Lusk 2012)**

The Kuz-Ram model (Cunningham 1983) can be utilized by using the same blast parameters collected by Lee and Lusk (2012). Input parameters for Equations 1–4 are shown in Table 2.

**Table 2. Kuz-Ram parameters**

| | | ANFO | Emulsion | |
|---|---|---|---|---|
| Diameter | d | 7.875 | 7.875 | in |
| | | 200 | 200 | mm |
| Burden | B | 17 | 20 | ft |
| | | 5.182 | 6.097 | m |
| Spacing | S | 18 | 20 | ft |
| | | 5.487 | 6.097 | m |
| Column height | L | 33 | 33 | ft |
| | | 10.06 | 10.06 | m |
| Charge weight | Q | 394.9 | 580.7 | lb |
| | | 179.5 | 263.95 | kg |
| Powder factor | k | 1.06 | 1.19 | lb/yd$^3$ |
| | | 0.63 | 0.707 | kg/m$^3$ |
| RWS | | 100 | 107 | % ANFO |

**Table 3. Comparison of mean particle size for calculated and analyzed size distributions**

| Explosive | $d_{50}$ Calculated (in) | $d_{50}$ Analyzed (in) |
|---|---|---|
| ANFO | 12 | 11 |
| Emulsion | 10.5 | 9 |

Figures 7 and 8 show comparisons of the calculated size distribution using the Kuz-Ram model with the average WipFrag photo analyzed for sized distribution for ANFO and emulsion.

Figures 6 and 7 clearly show the lack of inclusion of fines in photographic analysis; despite this the main curve of the graph has a relatively good fit between the calculated and analyzed distributions for both ANFO and emulsion. If the calculated and analyzed size distributions were compared to actual sieve data, it is hypothesized that the fines end of the curve will be between that already shown. This is due to the calculated models' underestimation of fines, and the fact that the photographic image analysis model has not considered the fines end of the spectrum at all. Mean particle sizes are shown in Table 3, the close proximity of values gives a good

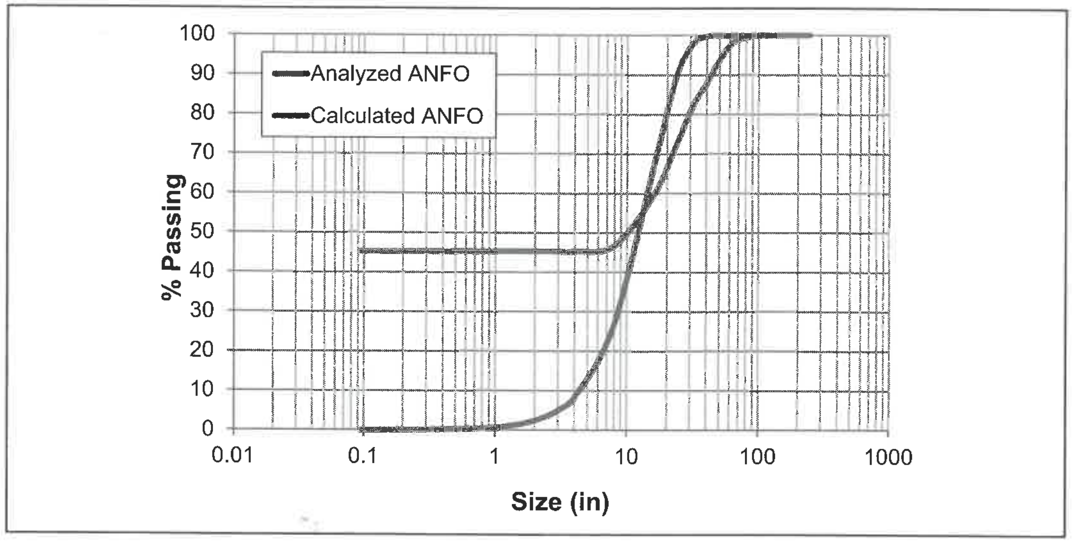

Figure 7. Comparison of calculated and analyzed size distribution for ANFO shot

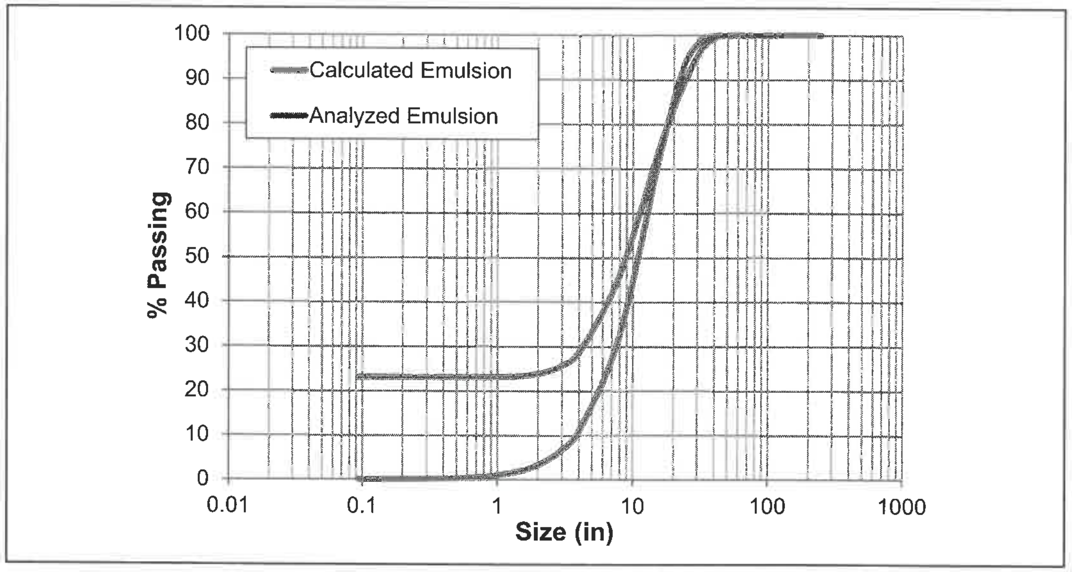

Figure 8. Comparison of calculated and analyzed size distribution for emulsion shot

indication that the Kuz-Ram model can estimate a reasonable average based solely on blast design parameters. The uniform size distribution of the Rosin-Rammler distribution and cost analysis based on time studies governed at a specific mine site can therefore give a good estimation as to the cost involved from mine to fill through obtaining different optimum size distributions.

## CONCLUSION

Further research through the ARIES project can potentially produce the input parameters similar to that in Table 4 for optimum particle sizes to minimize water quality effects from fill material. The shape and size distribution can be altered though blast design parameters and a reasonable distribution can be calculated using the Kuz-Ram model (Cunningham 1983). Ideally, a number of tables specific for each layer in the drain and filter system for grey sandstone are required. Cost analysis on the ability to adapt a blast design to produce the quantities required for a single layer in the filter system should be carried out and studies as to whether enough of the specified material is available at one site.

Table 4. Recommended values for specific use in mining

| | Property | Fill | Filter | Stability | Weathering Protection (erosion control) |
|---|---|---|---|---|---|
| Blast induced properties | Shape | | | | |
| | Size Distribution | | | | |
| | Density | | | | |
| | Porosity | | | | |
| | Resistance to weathering | | | | |

It has been proven that optimizing specific particle sizes for final use is possible though known blast design parameters and explosive type. Parameters from Table 4 to minimize environmental effects with respect to water quality, could however have a negative effect on other environmental factors, such as air quality (Lashgari et al. 2012). An optimum balance between cost, production and environmental issues should be found, similar to that discussed for productivity at an aggregate quarry by Hissem (2013).

Further research into the specific sizes required for minimizing water contamination in order to determine the actual cost and negative effects with respect to other environmental effects such as air quality is required before it can be determined whether the benefits will outweigh the possible increase in costs. Surface coal mines can use the concept outlines in this paper to optimize operations through mine to fill.

## ACKOWLEDGMENT

This study was sponsored by the Appalachian Research Initiative for Environmental Science (ARIES). The views, opinions and recommendations expressed herein are solely those of the authors and do not imply any endorsement by ARIES employees, other ARIES-affiliated researchers or industrial members. Information about ARIES can be found at http://www.energy.vt.edu/ARIES. Their financial contribution is gratefully acknowledged.

## REFERENCES

Adhikari, G.R., Venkatesh, H.S., Theresraj, A.I. Roy, S., Balachander, R. Jain, N.K., and Gupta, R.N., *Role of Blast Design Parameters on Ground Vibration and Correlation of Vibration Levels to Blasting Damage to Surface Structures.* National Institute of Rock Mechanics, September, 2005.

Bajpayee, T.S., Bhatt, S.K. "Fatal Accidents due to Flyrock and Lack of Blasting Area Security and Working Practices in Mining," Pittsburgh, Pennsylvania: National Institute for Occupational Safety and Health, 2003.

Bajpayee, T.S., Verakis, H.C., Lobb, T.E., "An Analysis and Prevention of Flyrock Accidents in Surface Blasting Operations," Center for Disease Control, 2004.

Blair, B.E., and Duvall, W.I., *Evaluation of Gages for Measuring Displacement, Velocity, and Acceleration of Seismic Pulses.* United States Department of the Interior—Bureau of Mines, Report of Investigations 5073, Washington, D.C., April 1942.

Chaiken, R.F., Cook, E. B, Ruhe, T.C., "Toxic Fumes from Explosives: Ammonium Nitrate-Fuel Oil Mixtures," 1974.

Clark, D., Larson, B., and Lande, G., *Vibration: Its Effect & Measurement Techniques at or Near Dwellings.* VME-Nitro Consult, Inc. Louisville, Kentucky 1983.

Cunningham, C.V.B., *The Kuz-Ram Fragmentation Model—20 Years On.* Briighton Conference Proceedings 2005, African Explosives Limited, Modderfontein, South Africa, 2005: 201–210.

Dick, R.A., "A Review of the Federal Surface Coal Mine Blasting Regulations," Proceedings of the Annual Conference on Explosives and Blasting Technique, 1979.

Ash, R.L., "Good Blasting Practice: Need for Uniform Standards," Proceedings of the Annual Conference on Explosives and Blasting Technique, 1975.

Djordjevic, N., A *Two-Component Model of Blast Fragmentation*. The AusIMM Proceedings, November, 2 1999: 9–13.

Duvall, W.I., and Fogelson, D.E., *Review of Criteria for Estimating Damage to Residences from Blasting Vibrations*. United States Department of the Interior—Bureau of Mines, Report of Investigations 5968, Washington, D.C., 1962.

Edwards, A.T., Northwood, T.D., *Experimental Studies of the Effects of Blasting on Structures*. The Engineer: Technical Contributors Section, September 30, 1960: 538–546.

Exedaktylos, G.E., C. Haycocks, Y. Zhou, "*Computer-Aided Blast Fragmentation Prediction*," Proceedings of the Annual Conference on Explosives and Blasting Technique, 1989.

Fletcher, L.R., D.V. D'Andrea, "Control of Flyrock in Blasting," Proceedings of the Annual Conference on Explosives and Blasting Technique, 1986.

Hissem, D. W, "How to Improve Safety, Create Value, and Maximize Profit in the 'New Economy,' Proceedings of the Annual Conference on Explosives and Blasting Technique, 2013.

Ireland, A. T., *Design of Air-Blast Meter and Calibrating Equipment*. United States Department of the Interior—Bureau of Mines, Technical Paper 635, Washington, D.C., 1942.

Kanchibotla, S.S., W., Valery, "*Mine to Mill Process Integration and Optimization—Benefits and Challenges*," Proceedings of the Annual Conference on Explosives and Blasting Technique, 2010.

Kanchibotla, S. S, Valery, W, and Morrell, S. Modelling Fines in Blasting Fragmentation and its Impact on Crushing and Grinding. Explo '99, Kalgoorlie, WA, 7–11 November, 1999: 137–144.

Kleine, T.H., A.R. Cameron, "A Blast Fragmentation Measurement and Prediction System for Blast Optimization," Proceedings of the Annual Conference on Explosives and Blasting Technique, 1997.

Kopp, J.W., Siskind, D.E., *Effects of Millisecond-Delay Intervals on Vibration and Airblast From Surface Coal Mine Blasting*. United States Department of the Interior—Bureau of Mines, Report of Investigations 9026, Washington, D.C., 1986.

Kuznetsov, V.M., The Mean Diameter of the Fragments Formed by Blasting, Institute of Mining, Siberian Branch, Academy of Sciences of the USSR, Novosibirsk, October 17, 1972.

Lashgari, A., Johnson., C.E., Kecojevic, V., Lusk, B.T., Hoffman, J.M., *NOx Emission of Equipment and Blasting Agents in Surface Coal Mining*. Appalachian Research Initiative for Environmental Science, 2012.

Lee, F.W., Thoenen, J.R., and Windes, S.L., *Earth Vibrations Caused by Quarry Blasting*, Report of Investigations, Department of the Interior—Bureau of Mines, November 1936.

Lee, N. and Lusk, B.T., ANFO vs. 100% Emulsion: Quantitative Assessment of Performance with Constant Drilling and Blasting Costs, Blasting and Fragmentation, Vol. 6 No. 1, November, 2012: 1–22.

Lilly, P. A, An Emperical Method of Assessing Rock Mass Blastability, The AusIMM/IE Aust Newman Combined Group, Large Open Pit Mining Conference, University of Queensland, October 1986: 89–92.

Little, T.N., "Flyrock Risk" Carine, Australia: TNL Consultants, 2007.

MacKenzie, A.S., Cong. J., *Cost of Explosives—Do You Evaluate it Properly?* May 1966: 32–41.

Madearis, K., The Development of Rational Damage Criteria for Low-Rise Structures Subjected to Blasting Vibrations. Kenneth Medearis Associates, Research, Engineering, Computer Consultants, Fort Collins, Colorado, June 22–24, 1977.

Mainiero, R.J. 1997. A Technique for Measuring Toxic Gases Produced by Blasting Agents. Proceedings of the Twenty Third Annual Conference on Explosives and Blasting Technique, Las Vegas.

Nicholls, H.R., Johnson, C.F., and Duvall, W.I., *Blasting Vibrations and Their Effects on Structures*. United States Department of the Interior—Bureau of Mines, Bulletin 656, Washington, D.C., 1971.

Northwood, T.D., Crawford, R.., and Edwards, A.T., Blasting Vibrations and Building Damage. The Engineer: Technical Contributors Section, May 31, 1963: 973–978.

Onederra, I, Bailey, V, Cavanough, G, Torrance, A., "Understanding main Causes of Nitrogen Oxide fumes in Surface Blasting," Institute of Materials, Mineral and Mining, 2012.

Ouchterlony, F., The Swebrec Function: Linking Fragmentation by Blasting and Crushing. Institute of Materials, Minerals and Mining & Australian Institute of Mining and Metallurgy, Stockholm, Sweden, 2005: Vol 114, A29–A44.

Ozdemir, K., Kahriman, A., Ozer, U., and Turner, G., Relation Between Excavator Bucket Loading Time and Particle Size Distribution of Shot Rock. Proceedings of the Annual Conference on Explosives and Blasting Technique, Vol 1, ISEE, 2007.

Persson, G, Persson, P.A., "Estimation of Toxic Fume Characteristics of Explosives from Steel Tube Blasting," Propellants and Explosives, Vol. 5., 1980.

Rollins, R. R and Wang, S., Fragmentation prediction in bench blasting The 3rd International Symp. on Rock fragmentation by blasting, Brisbane, Australia, August 26–31, 1990: 195–199.

Schettler, L, Brashear., S., "Effect of Water on ANFO/Emulsion Blends in Surface Mine Blasting," Proceedings of the Twenty-Second Annual Conference on Explosives and Blasting Technique, Orlando, FL, February 4–8, 1996.

Shaw, D.E., *Evaluation of Potential Blasting-Induced Damage to the Meason House*. 1989.

Siskind, D.E., Crum, S.V., Otterness, R.E., and Kopp, J.W., *Comparative Study of Blasting Vibrations From Indiana Surface Coal Mines*. United States Department of the Interior—Bureau of Mines, Report of Investigations 9226, Washington, D.C., 1989.

Siskind, D.E., Crum, S.V., and Pils, M.N., *Blast Vibrations and Other Potential Causes of Damage in Homes Near a Large Surface Coal Mine in Indiana*. United States Department of the Interior—Bureau of Mines, Report of Investigations 9455, Washington, D.C. 1993.

Siskind, D.E., Stachura, V.J., Stagg, M.S., and Kopp, J.W., *Structure Response and Damage Produced by Airblast From Surface Mining*. United States Department of the Interior—Bureau of Mines, Report of Investigations 8508, Washington, D.C., 1981.

Siskind, D.E., Stachura, V.J., Nutting, M.J., *The Generation of Low-Frequency Long-Duration Vibrations from Surface Mine Blasting at Blandford, IN*. United States Department of the Interior—Bureau of Mines. November 15, 1985.

Siskind, D.E., Stagg, M.S., *Assesment of Blasting Vibration Impacts from Quarry Blasting in Dade County*. D.E. Siskind & Associates, LLC. May 10, 2000.

Siskind, D.E., Stagg, M.S., *Blast Vibration Measurements Near and On Structure Foundations*. United States Department of the Interior—Bureau of Mines, Report of Investigations 8969, Washington, D.C., 1985.

Stachura, V.J., Siskind, D.E., Engler, A.J., *Airblast Instrumentation and Measurement Techniques for Surface Mine Blasting*. United States Department of the Interior—Bureau of Mines, Report of Investigations 8508, Washington, D.C., 1981.

Stachura, V.J., Fletcher, L.R., and Peltier, M.A., *Delayed Blasting Tests to Improve Highwall Stability—A Final Report*. United States Department of the Interior—Bureau of Mines, Report of Investigations 9008, Washington, D.C., 1986.

Stagg, M.S., Siskind, D.E., Stevens, M.G., and Dowding, C.H., *Effects of Repeated Blasting on a Wood-Frame House*. United States Department of the Interior—Bureau of Mines, Report of Investigations 8896, Washington, D.C., 1986.

Watson, R.W., J. Roth, "A Review of Blasting Accidents in Surface Mining," Proceedings of the Annual Conference on Explosives and Blasting Technique, 1978.

Williams, M.A., "Mining to Reduce Future Environmental Liabilities," Fifth High-Tech Seminar Blasting Technology Instrumentation and Explosives Applications, New Orleans, Louisiana, 1994