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Effect of rate of sumping on fragmentation process in laboratory rotary cutting simulator

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Effect of Rate of Sumping on Fragmentation Process
in Laboratory Rotary Cutting Simulator

Muralidharan Venkataraman

Thesis Submitted to the
College of Mineral and Energy Resources at
West Virginia University

In Partial Fulfillment of the Requirements
for the Degree of

Master of Science
in
Mining Engineering

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2003

Keywords: Bit design, Specific energy, Cutting tool, Cutting drum, Mining Cutting drum,
Coal Cutting Simulation

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ABSTRACT

Effect of Rate of Sumping on Fragmentation Process in Laboratory Rotary Cutting Simulator

Muralidharan Venkataraman

This study was done to examine the fragmentation process and to improve sumping. Research has demonstrated that specific energy and specific respirable dust must be kept minimum to produce the optimum parameters of the rock/coal breakage process and to attain maximum sumping. There are three major elements affecting the efficiency of the cutting head namely: 1) Geometry and size of the cutting tool, 2) Geometry of the drum and lacing and arrangements of the tools on the drum and 3) Effect of rate of advance /dynamic impacts. The emphasis is made on the rate of advance utilizing a miniature rotary cutting simulator. Experiments were repeated with different bit spacing to depth of cut ratio's in order to maximum sumping and the results were analyzed with special reference to specific respirable dust and specific energy. Experiments were also repeated with a newly designed bit and the results were compared with the conventional bit used in the experiments.

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**Dedicated
To
My Parents**

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Introduction:

The high demand for coal production has increased the need for mechanized coal cutting in underground coalmines. Continuous Miner's have been used in the United States for nearly decades, and currently more than 2000 underground miners are in operation. Almost half of the underground coalmine production of the country is by continuous miners. Figure 1 shows the total underground coal production in the United States for the year 1999 [1].

Figure 1. Shows the Total Underground Coal Production in the United States for the year 1999 [1].

These cutting machines which were introduced to increase the production and productivity have also increased the amount of respirable dust generated in the cutting process. The bit-coal/rock interaction has directly caused “Coal Miners Pneumoconiosis” which is also called as “black lung” disease. Rock cutting also produces fine dust accretion which results in “silicosis” and many occupational diseases like “siderosis”, “asbestosis” etc. Millions of dollars are spent in the form of compensation for respirable dust related diseases. A world report by NIOSH on work related lung disease investigations show that a total of 13,744 deaths [2]. The amount of silica and respirable dust generated by excavating coal and cutting roofs with continuous miners is the major concern for the industry.

The efficient bit design and cutting sequences can be a solution to these problems. The appropriate bit design is accomplished through a maneuver of a number of bit-related parameters including bit geometry, mounting configuration on the cutting head, bit

spacing and cutting depth etc. Improving the fragmentation process by understanding the mechanisms of coal/rock breakage will not only reduce respirable dust at the face, it will also reduce dust liberated during the secondary handling such as loading and transportation etc.

1.2 Problem definition:

Cutting bits are arranged in a crescent shaped path on the cutting head of the continuous mining machine, the bit's depth of cut vary along the cutting path starting from zero reaching a maximum falling back to zero [3]. This study was conducted with a view to remove the land/ridge between two adjacent cuts to provide a clean-cut face for the subsequent cutting cycle. The cutting parameters, which mainly influence the cutting process, are bit spacing, depth of cut and bit geometry. The bit geometry parameters that influence the cutting process are angle of the bit tip, bit tip size etc.

The continuous mining machines employ a rotary cutting technique. The main cutting parameters that influence the cutting efficiency of a continuous miner include bit spacing, depth of cut, bit geometry. For the purpose of the current studies the experiments were conducted utilizing an Automated Rotary Coal/rock Cutting Simulator (ARCCS) designed and developed by Khair [4] in the Rock Mechanics Laboratories at the West Virginia University. The ARCCS machine has arrangements to vary the RPM, penetration rate of the cutting head, depth of cut and bit spacing. It also has the arrangements to record these parameters and cutting pressure on a chart plotter. Through a correct combination of bit spacing and depth of cut two adjacent grooves starts interacting and the land/ridge between the two cuts can be removed which will result in large chip formation and less dust generation. If these lands/ridges can be removed effectively then the amount of respirable dust generated will be reduced considerably. So the experiments were conducted with an objective to produce clean-cut face using several conical and wedge shaped bits with different bit tip angles and bit tip sizes.

Research has demonstrated that specific energy and specific respirable dust must be kept at a minimum to produce the optimum parameters of the rock/coal breakage process and to attain maximum sumping. There are three major elements affecting the efficiency of the cutting head namely: 1) Geometry and size of the cutting tool, 2) Geometry of the drum and lacing and arrangements of the tools on the drum and 3) The

effect of rate of advance/dynamic impacts. Research investigates the influences of the above major element in the laboratory; however emphasis will be made on the rate of advance utilizing the ARCCS. Experiments were repeated with different bit spacing to depth of cut ratio's in order to attain maximum sumping and the results were analyzed with reference to specific respirable dust and specific energy.

Specific respirable dust is defined as the amount of dust generated in cutting a unit mass of rock/coal. Specific energy is defined as the amount of energy consumed in cutting a unit mass of rock/coal.

2. LITERATURE REVIEW

Since the introduction of continuous miners in 1950's, not much change has been made in the cutting drum design for efficient excavation and reduced respirable dust generation.

The problem in continuous miner head/drum is mainly associated with bit/tool and drum geometry. The bit/tool tips and the bodies are not designed properly, resulting in inefficient performance of machine and tools producing high level of noise and fine particles and generating enormous amounts of respirable dust. In a typical continuous miners drum, the bits cut face randomly at the contact position during first revolution and their cutting ability mainly depend on the geometry of the bits.

In the past, enormous research has been carried out to select the design parameters for cutting tools on a trial and error basis [5]. The mining industry is yet to receive a solution, which could provide optimum parameters for coal/rock cutting in underground coalmines. A few metals were tested at USBM [5] for their incendiarity in methane air explosive mixtures. The results have suggested that materials like polycarbonate resin, an ultra high molecular weight polyethylene, and zinc alloys were potential metals that could be used. But these were not acceptable of holding the carbide tips during coal/rock cutting. Nickel-based alloys proved to be safer than iron-based alloys as far as ignition was concerned. Research continued to find proper bit tip to prolong the life of the bit and reduce friction generation. There are two shapes of cutting bits commonly utilized, namely, wedge type and point attack type. Although point attack type bits are used most frequently in the US, research indicates point attack bits suffer a lot of bit tip wear and

damage. This is largely due to their inefficient rubbing contact with the wall of the cut groove (ridges/lands) as they profile.

Bit wear can be defined as the removal of material from the surface as a result of mechanical action. The mechanism of bit wear can be adhesion, abrasion, oxidation, or diffusion depending on cutting conditions. A study was carried out to study the principles of bit wear and dust generation [6]. In this study four types of point attack/conical used bits were obtained from different underground coalmines. The analysis showed that many bits did not rotate properly during cutting process. As rock and coal debris plunge into the spacing between the bit blocks and bits, lock in of the bit into the bit block results. The same study showed that worn bits with 15% weight loss generated about 26% more dust than the new bits. Researchers at USBM [7] indicated that the rate and form of bit wear highly depend on bit temperature. Diffusive wear becomes the dominant form when bit temperature is higher than the critical temperature. Bit velocity is the main parameter to influence the bit temperature. The wear rate of steel, steelate and carbide tools is reported to be independent of bit velocity when the bit velocity is below a critical value of 165 to 220 ft/min. wear was observed to increase very rapidly above the critical velocities [7]. Since bit velocity increases the temperature of the bit, it is necessary to insure that bit velocity is below the critical value. However, low velocity will reduce production.

The major problems in the cutting action of the rotary cutting drum, which excavates the cutting face, are the following: 1. Non-uniformity of the cutting depth for each individual bit along the cutting bit, 2. Generating secondary dust, which may be much more than the primary dust generation due to cutting action, 3. Excavating material in a confined state/solid face without pre-cut free faces/slots. In a rotary cutting action the shape of the groove along the path of an individual bit resembles a crescent moon (see figure 2). Researchers in USBM addressed the problem of non-linear cutting action of the rotary technology. At the beginning and at the ends of the cutting path both drums have a similar shallow depth of cut (see figure 3). Perhaps the major design philosophy was to reduce the length of the low recovery; shallow depth of cut region along the cutting path of the individual cutting bit on the drum. A comparison of laboratory experiment utilizing drums of the same size, indicated that when both drums have reached 75% of the maximum depth of cut, the rotary drum has removed approximately 33% of the total volume, while the linear cutting has taken only 15% in the shallow cutting region [8]. However, under variable seam thickness, which requires both sumping and shearing, the

difference in total dust generation may not be as significant, comparing this design to modify the regrinding process of the typical rotary cutting drum. The linear cutting drum cuts material to an open face most of the time with minimal secondary fragmentation. The linear cutting drum did not get out of laboratory because of two major reasons: a) the concept was totally unfamiliar to the mining industry; b) the drum required a very high torque gear box to be practically utilized.

In typical continuous miner drum, the recovered coal/rock and coal from the previous cutting cycle have to be transported through the circumference of the cutting drum, subjecting coal/rock to regrinding. Regrinding as the action of the drumhead on fragmented material caught between the drum and the face, particles impacted with each other and with the bits, before discharging during sump cutting. Such regrinding comminutes the coal/rock material utilizing kinetic energy, thus creating a great amount of respirable dust (secondary dust generation)[8] laboratory study was carried out at WVU to study dust generation due to regrinding [9]. The assessments of dust generation, in this study indicated that dust generation by regrinding depends on the size of the particles being cut during primary excavation (i.e., cut by first line of bits). Higher dust

Figure 2. Simplified diagram of crushing and chip formation when cutting with continuous miner [3]

Figure 3. Shows the ends of the cutting path of the laboratory cutting drum showing a crescent shaped depth of cut [3]

concentrating coefficients were obtained by regrinding finer particles. Increasing depth of cut creates less fine particles and reduces dust generation by regrinding. Among those parameters considered in this study the depth of sump has most significant effect on dust generation by regrinding. Dust generation also significantly depends on hard groove grindability index. The coal with higher grindability index has higher dust concentration coefficients. Higher velocity of cutting head causes higher dust concentration. Dust concentration by regrinding is linearly proportional to the amount of coal left for regrinding [9]. This study recommends that loading the entire coal design removed/excavated in each cutting cycle will help to reduce regrinding. It has been said that “using blunt, high speed bits, (continuous mining machines) probably are the best machines for forming dust that could be invented, except for a grinding stone” [8]. This concern has been substantiated in a study by USBM [8]. In this study it was shown that a continuous miner produces 70% of total dust while sumping, and only 20% while shearing. The remaining 10% is attributed to gathering and loading. These differences in dust values between sump and shear for a continuous miner may be attributed to 1) less breakout of the coal to a free face on sump than in shear and 2) the regrinding action of the drum head on fragmented material. These differences suggest that to reduce dust

generation we may have to reduce regrinding by eliminating the sumping action and/or by cutting to an open face all the time [10]. Cutting to an open face is one of the innovative features of the proposed research study.

2.1 RESEARCH ON ROCK/COAL CUTTING:

Efficient rock/coal cutting is a result of the optimum use of available resources in a continuous mining system. Research has demonstrated that specific energy and specific respirable dust must be kept at minimum to produce the optimum parameters of the rock/coal breakage process.

2.2 MECHANISMS OF ROCK/COAL FRAGMENTATION:

Quasi-static and dynamic forces govern the fracturing process. In recent study by Khair et.al. [10] The fracturing process in Tennessee sandstone specimen, subjected by wedge indenter, exhibited holographically. From the failure process point of view, it's obvious that initial wedge-rock interaction results in high stress concentration at the area of contact zone, results in causing microfailure of material in the vicinity of the contact zone (between wedge and rock).

As the stress exceeds the strength of the material, it results in pulverization of the interface zone. As the loading continues, the wedge penetrate further and the pulverization of contact zone. Interface extends until sufficient tensile stress (splitting stress) develop to initiate failure, and at that instance the extension of the pulverization zone stops, hence failure of the specimen occurs. The thickness of the pulverization zone in the wedge-rock interface mainly depends on two factors: 1) material characteristics such as brittle, ductile behavior of material in particular cracks, discontinuities, porosity and flaws exist in the material, which are more susceptible to causing stress concentration and allow wedge to penetrate deeper into the material. To extrapolate this fact further, ductile/soft material requires more deeper wedge penetration prior to splitting/fragmentation than brittle/harder material; 2) wedge angle, the higher the wedge angle less wedge penetration and less crushed material produced.

Fracture process in coal/rock by rotary cutting designed by Khair showed that the dynamic forces causes fracture formation and fracture extension, while the quasi-static forces are responsible for grading the fracture surface. Observations during the tests indicated that after the cutting head induces certain fracture (different intensities,

magnitudes and lengths), its rotational velocity slows down. Analyzing the cutting action, when the bit enters the coal it indents and compresses the coal under it and shears off the fragments. This process yields coal fragments, coarse and fine, and dust particles. The key to analyzing and understanding the source of dust generation is to identify the different phases of the cutting process and to correlate them with the particles. Previous investigators have observed that during the indentation of a cutting bit into a brittle material, two phases occur. These are called the crushing phase and chipping phase. This was later extended to linear cutting by observing the cutting action under very low speed [11]. In this study it was theorized that when the bit first hits the rock inelastic subsurface cracking takes place. Such an action leads to crushing due to coalescence of the cracks. Crushing and subsurface cracking will produce fine fragments and dust. It was observed that the cutting and thrust forces build up and increase during the crushing/pulverizing phase of the material and drop when a major crack is generated, resulting in chip formation.

3. CUTTING PARAMETERS:

The important parameters of rock/coal cutting are 1) attack angles, 2) bit geometry 3) depth of cut 4) bit spacing.

1. Bit Attack Angle: Research has been carried out by Khair, et.al. [19] utilizing four different attack angles, 15° , 30° , 45° and 60° , were used by in this study (Figure 4). The most ideal condition for force transmission by the bit to the coal will be a 30° attack angle, where the area of contact between the bit and coal is at a minimum and causes a high stress concentration in the coal block. As a result, less force is required to break the coal. The smaller attack angle will not only require a larger normal force(thrust) to penetrate the coal, consequently resulting in more friction heat, especially during the quasi-static loading condition (grading).

The second best condition would be the 45° angle of attack. The 60° angle of break is similar to the 15° ; however in this case the front portion of the bit will have a larger surface area of contact with the coal. Its influence on fragmentation will be during the dynamic loading cycle and the larger area of contact will make the bits behave as if it were blunt. This study has been carried out under shallow

Figure 4. Testing bits tested with different attack angles

- depth of cut, however under larger depth of cut, 45° attack angle will be more preferable, because the tip of the bit with least area of contact with material to be cut, will remain in contact, hence improving the efficiency of the tool.
2. Bit geometry: Conical bit are commonly used in USA mining industry and discussions are focused in this type of bits. In regards to bit geometry, there are two elements associated with bit geometry, 1) bit tip and 2) bit body. Research has been carried out by many investigators to characterize bit geometry i.e. bit tip angle and size but bit body geometry and stream lining of bit tip and body for efficient fragmentation, durability, ignition respirable dust generation, specific energy consumption, noise generation, breakout angle and multi bit interaction.
 3. Depth of cut: Past research indicated that as the depth of cut is increasing the specific respirable dust reduces. Deeper cutting enable interaction between adjacent cuts and help produce larger chips of the material. Hanson and Reopke [12] found that the average cutting force increase with increase in depth of cut while the specific respirable dust and specific energy decreases with depth of cut.

It is known that a proper depth of cut to bit spacing ratio reduces specific dust generation. This ratio depends in machine cutting parameters and physical and mechanical properties of rock [13]. Research work was conducted by a number of people on rotary cutting bits. Research at USBM [14] demonstrated that the specific energy and airborne dust (ARD) decrease significantly as the cutting depth increases and the optimum tool spacing to cutting depth ratio ranges from 2 to 3. Further study by the USBM researchers [14] concluded that different bits do not effect the ARD as significantly as cutting depth or specific energy, but

various bits have different forces and energy requirements necessary to maintain a prescribed cutting depth.

Barker [15], Pomeroy and Brown [16] reported that optimum spacing depends on depth of cut. For a cut spacing at which neighboring grooves interact, the cutting forces decreases after reaching a maximum. The maximum normally corresponds to the condition of high product volume, low specific energy and low dust generation. Research also indicated that specific energy decreases with depth and spacing.

Many studies have addressed the influences of cutting parameters on respirable dust generation during coal cutting process. Research was conducted at WVU [17] utilizing a series of single and multiple bit experiments on coal using a laboratory scale cutting machine in order to investigate the sources of respirable dust generation both at macro and micro levels. Khair, et.al [18] documented several issues in rock cutting process that need to be addressed and the concern for respirable dust in the report submitted to USBM. The Bureau of Mines conducted a series of experiments using four different coal types to determine the effect of attack angle and asymmetric bit wear on airborne respirable dust (ARD) generated by point attack bits and in energy consumption [11]. They established that the depth of cut had significant effect on the respirable dust and specific energy.

Research conducted at WVU indicates that specific respirable dust increased with increasing bit spacing in rotary cutting. As the bit spacing increases the grooves made by the bit do not interact and hence the ridges do not break. Instead of the formation of major chips, regrinding occurs in the grooves producing significant amount of fine dust. As the cutting depth increases, the amount of respirable dust generated reduced as deeper cuts enable the interaction of adjacent cuts and help in production of major chips [13].

A series of preliminary laboratory experiments were carried out at the Department of Mining Engineering at WVU [19]. Figures 5 and 6 show experimental setup. In this study a series of experiments were run with a 3-inch bit spacing. Three bits were mounted in a echelon pattern and a 2.5-3 inch deep cut was made without breaking the boundary walls/ledges between the bit paths. Series of tests were carried out for the 15°, 30°, 45° and 60° attack angles. With

1.5 inch spacing and five bits mounted in an echelon pattern, the side walls/ridges of bit path were broken when the coal blocks were tested in both face and butt cleat direction. In these experiments the fracture surface was more regular when tested against butt cleat, walls/ridges between the cutting paths broke only partially and irregularly. A total breakage of the walls/ridges created a free face, thus reducing the required resultant forces to be cut and coal [19]. As it was indicated earlier that depth of cut not only reduces primary and secondary dust generation, but also

Figure 5. Third generation of an Automated Rotary Coal Cutting Simulator (ARCCS).

Figure 6. The experimental setup

reduces specific energy depending on bit geometry. A series of preliminary experiments were carried out by Khair at the Academy of Sciences of Czech Republic, Institute of Geonics, Ostrava, Czech Republic [18]. Among the tested bits, US2 performed well. This high performance of the US2 type bit was due to two geometric parameters, namely high clearance angle and prism shape of the cutting face of the bit, which further reduced the surface contact area of the bit during the cutting process. These two factors reduced the specific energy consumption for the bit, in particular, under deeper cutting condition (i.e., at 3 mm depth of cut, specific energy consumed by the bit is 18.4 MJ/m^3 , and at an 18mm depth of cut, the consumed specific energy was reduced to 24.1 MJ/m^3 with a corresponding mean nominal force to mean cutting force ratio of 0.91 and 0.53 respectively). Results also indicate that specific energy consumed by the bit decreases with depth of cut.

4. Bit Spacing:

Linear cutting experiment has been carried out in order to study the influence of bit spacing on the energy consumption and amount of noise produced during cutting [20]. The results indicate that the noise levels usually increase with an increase in the cut spacing to depth of cut ratio for individual bits. There is an increase in the noise level, energy consumption of 4.5% and 24.1% respectively when the bit spacing to cut depth ratio was increased from 1 to 2.

Furthermore the linear cutting indicated that the noise levels increase as the bit tip size increases. The noise levels increased by about 5 dB with a larger body and tip size. Therefore by an optimum bit spacing to depth of cut ratio and optimum bit tip size a reduction of upto 10 db of noise was resulted during cutting process. It should be emphasized that the bit tip size is not only parameter that effects bit performance but also geometry of bit tip and bit body a stream lined shape is important.

4. Sources of Dust Generation

Coal and rock are brittle materials. In the fracturing process of brittle materials, the material is actually subjected to compressive and shear stresses by which fine fragments and dust are produced. The mechanism by which these fine fragments and dust are produced were presented by Hartman [49].

A simple process relevant to the working of coal by a tool is the indentation of a flat coal surface by a rigid wedge. There is a crush zone of finely fractured material around the tip of the indenting wedge; extended outward from this crush zone are long fractures, usually with a prominent one which propagates ahead of the tool tip due to wedging action of the tool. The sequence of events, which result in this configuration, may be briefly summarized as in figure 7.

- Initial Loading: The sharp indenter induces a zone of inelastic deformation about the contact point by crushing off all surface irregularities.
- Critical zone formation: At some critical indenter load a crack termed the median vent suddenly initiates below the indenter-coal contact point causing elastic deformation.
- Stable crack growth: Increasing the load further causes stable extension of the median vent.
- Initial unloading: The median vent begins to close.
- Residual Stress Cracking: Relaxation of deformed material within the contact zone just prior to removal of the indenter superimposes intense residual tensile stress upon the applied field. Sideways-extending cracks, termed lateral vents, begin to appear.
- Complete unloading: Lateral vents continue to extend to the free surface causing Chips.

Figure 7. Sequence of events which result in this configuration [49]

Depending on the magnitude of the load the crush zone increases. It is the material in this crush zone that becomes a major source of dust during subsequent cuts.

5. Analytical Studies

The slip-line theory of plasticity has been applied in the study of stress field indentation problems [21] extended the theory to the case of a plastic material using an yield condition based on the Mohr-Coulomb criteria. He showed that two families of characteristics exist which are inclined at an angle of $\pm (\beta/4 - \Phi/2)$, where Φ is defined as the angle of internal friction and β is half the angle of the wedge. The Mohr-Coulomb criterion was used to represent rock behavior because of its good first approximation with the experimental results and also for mathematical simplicity. Cheatham [21] used the same theory to study the maximum and minimum forces required to penetrate in to a rock using a wedge type bit. These forces correspond to the limiting cases of rough and smooth bit-rock interface. Parieau and Fairhurst [22] used the same theory on a wedge

with smooth, frictional and rough interface conditions. Clark et al. [23] extended the same theory to a blunt point, round point and cylindrical indentors using the same interface conditions.

Evans and Murrell [24] used two simple models, the difference between the two being the consideration of friction. In the first case the friction was neglected, penetration resistance q , was assumed to be equal to the compressive strength, q_0 per unit area.

This leads to the equation:

$$F = 2q_0hw \tan \beta$$

Where, F is the load, h is the penetration measured from the level of undisturbed coal surface, w is the width of the wedge and β is the half angle of the wedge. Experimental data on two different coal types was found to be in good agreement with the assumption that the penetration force equation becomes:

$$F = 2q_0hw \tan (\beta + \beta)$$

Where, β is the coefficient of friction between the tool and the coal.

Paul and Sikarskie [25] developed a two dimensional model which is symmetrical about the wedge axis and the fracture surface and in which the chip failure was assumed to be planar. Also the frictional force exerted by the wedge on the chip was assumed to be negligible. Mohr – coulomb failure criterion:

$$S_3 = \beta - \beta \alpha$$

was assumed along the chip failure plane. Here β and α are the shear and the normal stresses on the plane and S_3 is the shear strength of the coal. Both constant displacement rate and constant load tests were conducted. In a constant displacement rate test, the force rises during the crushing phase until a chip is formed (fracture criteria) and drops to zero (curve b of figure 8), while in the constant load test, the load remains constant after the chip is formed until the new equilibrium position is reached (curve c of figure 8). The experimental results of curve a in the figure 8 qualitatively resemble the force penetration curve b in the figure 8.

Figure 8. Shows experimental results of curve a [37]

Sikarskie and Cheatham [26] removed the planarity assumption of the chip surface and used a numerical approach to assess the “fracture function” which is conceptually equivalent to $|\beta| - \beta \alpha$ as a function of position around the wedge shaped indenter. When the maximum value of the fracture function reaches the critical value S_3 of the Mohr-Coulomb criterion, fracture initiates at the point where the maximum stress occurs.

Miller and Sikarskie [27] used a conical indenter on Indiana limestone and Barre granite. The chips are assumed to be conical shells. The same behavior was observed in the case of constant rate test as in the wedge-indenter case, but with the same linear crushing law the force at chipping becomes parabolic rather than linear penetration depth (figure 9). They also formulated equations to estimate the total volume of rock removed due to bit penetration.

$$V = (\beta d_i^3 \cot^2 \mu) / 3 \text{ for cone shaped indenter.}$$

$$V = (4d_i^2 \cot^2 \mu) / 3 \text{ for pyramid shape indenter.}$$

Where, V is the volume of crater, d_i is the depth of the i th cutting and μ is the failure angle. (Figure 9)

Figure 9. Shows the Force – Penetration Loading Curves [39].

Lundburg [28] used the Paul and Sikarskie's [25] model and conducted tests on Swedish Bohus granite. Seven indentors with apex angles in the range of 60° to 150° were tested. Results indicated that no chipping occurs for angles greater than 60° apex angle while the crushing was observed to be predominant. Nishimatsu [29] used the shear strength as the governing factor and analyzed the mechanics of coal cutting. He calculated the amount of plastic yield product during the cutting process. Sun et al. [30] and Bieniawski [31] used the fracture mechanics principles to explain the fundamentals of rock cutting process.

6. Conical Bits or Attack Bits

The precise mode of action of the point attack bits has not been studied as extensively as the wedge shaped bits. Strebig and Zeller [32] compared three wedge bits with two point attack bits. They concluded that bit type does not have significant effect on the dust generation. Roepke et al. [35] used four different types of point attack bits and concluded that smaller diameter bits with overall sharp points are more efficient (they require low specific energy). This could be attributed to the fact that the cavity created by the bit is less than the diameter of the bit body travelling in to the groove and hence rubs against the groove, thus creating more dust and consuming more energy.

Hurt and Evans [34] concluded that point attack bits consume higher specific energy and generate more respirable dust when compared to the wedge shaped bits, regardless of the

bit sharpness. However, specific force requirements for point attack bits reduced at higher depths. Geometry of the cutting bit was also studied. Hurt [34] noted that an angle of attack of 50° would require the minimum cutting force and a minimum back clearance angle of 12° was necessary for the point attack bits in place of 5° for wedge shaped tools.

7. Depth of cut

7.1 Point Attack Bits

Effect of depth of cut was studied by Strebig and Zeller [32] using point attack bits, they have found that specific air borne respirable dust reduces considerably with deep cutting.

7.2 Wedge Shaped Bits

Werblow [37] varied the depth of cut in wedge shaped bits and found that the mean peak force required increases linearly with increase in cutting depth. Coal yields increases with increase in depth of cut (Pomeroy and Brown, [38]), they have found that the energy consumption decreases with increasing depth of cut and rises after reaching a minimum, this minimum consumption of energy corresponds to the minimum production of fine particles.

8. Cut Spacing

Cut spacing is defined as the distance between centers of adjoining cuts in a sequence. There are two factors, which contribute to the removal of material from the face: (1) The cutting elements continue to penetrate in to the grooves and remove the material, (2) Neighboring grooves interact to remove the material in the form of large chips from the land/ridges between two adjacent grooves. The efficiency of this process depends on correct spacing, depth of cut and several other parameters like the tool size, thrust and the type of material.

Barker [15] have reported that the optimum spacing depends on the depth of cut. For a cut spacing at which neighboring grooves interact, the cutting forces decreases after reaching a maximum. This maximum normally corresponds to the optimum conditions of high volume, low specific energy and low specific dust. Cut spacing for the point attack bits have been studied by Roepke et al. [12], and suggested that a spacing to depth ratio of 2 to 3 to be optimal. Hurt and Evans reported that, the specific energy decreases with depth and spacing, rapidly at first and then more slowly. However, a proper space to

depth ratio which assures that each bit is taking as deep a depth as possible, with efficient breakout can be found through experimentation for any set of operating conditions.

Several other parameters like the cutting head velocity, confining pressure and cutting speed (rate of advance of the drum) effect the amount of respirable dust generated. Although considerable research had been conducted both experimentally and theoretically on rock cutting, most of those studies used linear cutting principle at a constant cutting depth and later the results were employed to rotary cutting. But Khair [41] designed a laboratory scale simulated continuous miner to investigate the rotary cutting concepts and to characterize the coal breakage. Khair et al. [41] presented several stages in chip formation and primary sources of dust generation during both coal and rock cutting utilizing the simulated continuous miner.

9. Theory of Rock Breakage

One of the fundamental theories of rock cutting was proposed by Evans et al. [42]. Evans's model of tensile rock failure described the penetration of a wedge into the buttock of coal. Several other researchers made use of this theory to explain the general failure phenomenon of rock breakage [43] Evans [44] proposed a modified theory of cutting force for point attack bits in which most of the concepts were retained from his earlier theory. The following equation provides the cutting force required for cutting the rock as a function of its both compressive strength and tensile strength.

$$P_c = (16 \beta l t d^2) / u \cos^2 \Delta$$

Where P_c is the cutting force exerted by the cone of the bit, u is the unconfined compressive strength, t is the tensile strength, Δ is the semi angle of the cone, l is the slant cutting depth of the point of interest, and d is the cutting depth.

Nishimatsu [45] used the Mohr-Coulomb criterion of failure for stress conditions during the formation of chip. Assuming the shear strength is the parameter governing failure, he provided an equation to predict the required cutting force, F_c .

$$F_c = (2 S_s d W \cos \cos(\mu - \Phi)) / (n+1) [1 - \sin(\beta \Phi + *)]$$

Where S_s is the shear strength of the rock, d is the depth of cut, W is the width of the pick, $*$ is the angle of internal friction, μ is the angle of friction of rock cutting, Φ is the rake angle, and n is the stress distribution factor.

10. METHODOLOGY

Literature review reveals that substantial quantities of dust are created by the process that follow the actual cutting of coal, including the crushing of pieces between the drum and the face, impact of pieces on the floor etc. However, it is important to know how much dust is being generated in the cutting process itself. Coal deposits are often encapsulated in sedimentary rocks such as shale, sandstone or limestone. During the extraction of coal, the roof and floor of the coal seams often consists of one of these rocks. It is a common occurrence to cut these rocks during the cutting of coal. Studies carried out using rock material such as Indiana limestone can be meaningful for analyzing coal and other equal strength materials. It should be noted that the Indiana limestone has been used in many research works and it has good directional homogeneity. Thus, for the purpose of current studies Indiana limestone is chosen.

The continuous mining machine employs rotary cutting technique. The main cutting parameters that influence the cutting efficiency of a continuous miner include bit spacing, depth of cut, bit geometry. For the purpose of the current studies an Automated Rotary Cutting Simulator (ARCCS) shown in figure 5 was used. This simulator enables the experimenter to simulate the *in situ* vertical and horizontal confining pressures and to vary several other operating parameters like the depth of cut, cut spacing, velocity of the cutting head etc.

The research work is essentially designed to investigate the relationship between the rate of advance/ sumping rate with cutting parameters like the cutting force, penetration force, depth of cut, bit spacing and the bit geometry parameters like the angle of the cutting tool, bit tip size with a view to reduce the amount of respirable dust generated in the cutting process. There is a land/ridge formed in between two adjacent grooves, if this land/ridge can be removed with minimum expense of energy then that cutting process will become efficient. If the spacing between two adjacent grooves is optimal then the two cuts will be interacting with each other and help in removing the land/ridge. If the land/ridge is removed in one cutting cycle then a clear-cut face will be provided for the subsequent cutting cycles and it helps in reducing the amount of respirable dust that is being generated.

11. Description of the ARCCS

A brief description of the major parts of the ARCCS is given in the following sections.

Main Frame:

The machine is mounted on a rectangular frame of 1.5 m x 1.1 m side dimensions and four legs. The legs are provided with wheels for easy maneuverability.

Confining Chamber:

The confining chamber is made of 1 in. thick steel. Inside dimensions are 76.2 cm x 50.8 cm x 17.78 cm (30 in x 20 in x 7 in). The confining pressure to the blocks of the material is applied by four hydraulic cylinders. Two of these were of 10 ton capacity each (which apply horizontal pressure), and other two were of 20 ton capacity (which apply vertical pressure). Hydraulic pressure to the cylinders was applied by two manually operated hydraulic pumps.

Cutting Drum:

The cutting drum is 17.78 cm (7.0 in) in diameter and 30.5 cm (12 in) in width. The metered hydraulic fluid flow gives the flexibility to rotate the drum at different rotations per minute. Advancing and retreating of the cutting drum is accomplished by two reversible hydraulic cylinders.

Stripchart recorder:

A model 1246 strip chart recorder is the main part of the data acquisition system with the ARCCS. An Acoustic Emission unit (AE) detection and monitoring system, was used to study the performance of the cutting tool, in terms of fracturing the rock block by the action of the bit. Figure 10 shows the strip chart recorder and AE unit used in this experimental study. The experimental data on cutting pressure, penetration pressure, and the depth of cut are fed to the strip chart recorder. The vertical confinement pressure was approximately 2000 psi. The horizontal confinement pressure was about 1/3 of the vertical confinement pressure. The maximum depth of cut was about 1.5 in.

Figure 10. Stripchart recorder used in the experiments.

Other important parts of the ARCCS are the movable frame arrangement, air current generating unit, automated control and monitoring system.

12. Physical and Mechanical Properties of Indiana Limestone

The Indiana limestone rock is obtained in blocks with dimensions of 19 in x 12.5 x 7 in. All the test blocks were finished to suit the testing conditions of the confining chamber of the ARCCS. The cutting bits were mounted on the cutting head and the attack angle of the bits was kept constant at 45° for all experiments. The Indiana limestone is popularly known as standard Buff and is oolitic limestone. It is a calcite cemented calcareous stone formed of shells and shell fragments, practically a non-crystalline in character. It possesses a remarkable uniformity of composition, texture and structure. Table 1 describes the physical and mechanical properties of this rock material obtained in the laboratory through standard test procedures.

Table 1 Physical and Mechanical properties of Indiana limestone

Rock Property	Value
Unconfined compressive strength, psi	4786.3
Young's modulus, psi	$2.51 * 10^6$
Tensile strength (Brazilian), psi	449.6

Direct Shear Strength, psi	565.6
Poisson's ratio	0.25
Specific gravity	2.2
Flexural strength (3 point loading), psi	1058.8

13. Data Acquisition Methods

The data acquisition system and the physical measurement devices are available in the rock/coal cutting laboratory. Using the facilities the following parameters were studied in each experiment:

- Cutting Pressure
- Penetration Pressure
- Cutting Depth
- Amount of Respirable dust generated
- Mass of rock cut product
- Number of AE generated during each experiment

A model 1246 strip chart recorder is the main part of the data acquisition system with the ARCCS. The experimental data on the cutting pressure, penetration pressure, and the depth of cut are fed to the strip chart recorder. Research suggest that an attack angle of 45° is an optimum and also has least significant effect on other bit related parameters [35]. So the angle of attack was kept at a constant 45° for all the experiments. The vertical confinement gage pressure was kept at approximately 2000 psi gage pressure. The horizontal confinement gage pressure was about 1/3 rd of the vertical confinement gage pressure. The maximum depth of cut was about 1.5 in. The advance rate of the cutting platform was kept at 0.525 mm/s. A number of experiments were conducted at 2.0in., 2.5 in., and 3.0 in. of bit spacing but the lands/ridges were not removed at those spacings. So the experiments were conducted at 0.5in., 1.0 in., and 1.5 in. of spacing and to a depth of cut of D inch where D is the depth of cut obtained during first cut followed by 1.5D and 2D respectively.

14. Dust Sampling

Series 296 type Marple personal cascade impactors were used to collect the respirable dust [46]. These impactors have six stages and a backup filter. They can give

complete, accurate aerodynamic particle size distributions. Two impactors, one at the middle and one at the bottom with respect to the cutting head, are mounted during every experiment. Du-pont air pumps were used to operate the cascade impactors. The air pumps were recharged to full before conducting each experiment. The suction rate of the air pumps was maintained at 2L/minute. The principle of operation of impactors is based on the flow entering the inlet cowl and accelerating through the six radial slots in the first stage. Particles larger than the cut point of the first stage impact on the perforated collection substrate. Then, the air stream flows through the narrower slots in the second stage of the impactors, smaller particles impact on the substrate in the second stage and so on. The width of the radial slots is constant for each substrate but is smaller for each succeeding stage. The jet velocity is higher for each succeeding, and smaller particles eventually acquire the sufficient momentum to impact on one of the stages.

The six stages of cascade impactor, stages 3 to 8, collect particles with different Geometric Mean Diameter (GMD) in each stage. Table 2 describes the GMD of different stages. The impactors were prepared 24 hours before they were used. The preparation includes the following: cleaning of each stage, cleaning the cowl, and evenly spraying the grease to form a film under the slots of the preceding stage. Model C-290MY Mylar media filters, 34 mm. in diameter were greased by model 290IGS Impaction Grease Sprayer. The original weight of the substrate was measured immediately before and after an experiment to the nearest 0.01 mg by a Sartorius type 2462, semiautomatic, electronic analytical balance with digital readout. The amount of settled dust generated for each experiment was collected in a chamber under the cutting head and was weighed subsequently. Figure 11 shows the cascade impactors used in the experiment and figure 12 shows the suction pumps used in the experiment.

Figure 11. Shows the cascade impactors used in the experiment

Figure 12. Shows the suction pumps used in the experiment

Table 2 Different stages and their GMD in a cascade impactor

Stage	Stage3	Stage4	Stage5	Stage6	Stage7
GMD microns	12.25	7.75	4.58	2.65	1.34

15. Characteristics of Cutting Bits

Conical and drag bits were used in this study. The conical bits used in the study were obtained from Kennametal Inc. of Bedford, Pennsylvania [47]. They were typically made of 15B35 steel and are simultaneously brazed and heat-treated. The tips composed of tungsten carbide. The insert has an average density of 14.6g/cm^3 , contains 8.2-8.8% of cobalt. Figure 13 shows the U76K cutting bit used in these experiments.

Figure 13. Shows the U76K used in the experiment [47].

16. Experimental Work

16.1 TESTING PROCEDURE

Experimental Work: The objective of these experiments were to remove the land/ridges in a cutting cycle which will reduce the amount of respirable dust generate. In order to assess the bit spacing, bit is tested one at a time at several spacings and kept at the same bit holder. Initial experiments were repeated with lesser rate of advance to achieve a maximum depth of cut of 1.5 inches. This rate of advance was increased from 0.07 inch/sec to 0.14 inch/sec and to 0.21 inch/sec and the respirable and settled dust were collected and was measured later. The resultant, cutting and penetration forces, specific dust and specific energy were calculated and also the final depth of cut was measured.

Free face plays an important role in cutting process. Thus by free face we define the performance of the bit when there was preexisting cuts on its sides and the effect on the performance when the spacing is 1.0 inch, 1.5 inch etc.

Performance of the new bit designed by Khair, Principal Investigator of this research were tested. These bits were designed with the analytical and experimental studies done before and were fabricated. Experiments were done utilizing this bit and the results were compared with the bits used before.

16.2 Analysis:

Khair [18] characterized failure of geologic material during bit – rock/coal interaction and concluded that, it depends mainly on three parameters: Bit geometry, Brittle-ductile characteristics of rock/coal material and confined state in the material. From mechanistic point of view, bit geometry translates to the stress concentration. Sharp bit, for a specific machine forces impose high stress concentration on the rock/coal, hence results in fracture development in the rock/coal. The sharper the bit is, bit penetrates deeper and fracture penetrate deeper with less crushing in the area of interface. On the other hand if the bit were too sharp it wouldn't last too long during cutting process in particular if the cutting material is too hard. However, dull bit will have larger area of contact with cutting material and requires more machine force to develop enough stress concentration to cause failure. Furthermore if the interface between bit-rock/coal is too much and the machine applied force is not sufficient to cause deep failure in the material, it will result in less fracture and more crushing/dust generation during cutting process. Therefore an optimum geometric shape for bit is required to result efficient performance of the

machine, prolong the life of the bit yet to produce sufficient fracture in the interface with least crushing/ dust generation. The optimum geometry of the bit also depends on the brittle-ductile characteristic of the cutting material. For particular bit geometry and machine force, bit will impose deeper and more fracture and less crushing on the brittle material such as rock and harder material, while on the coal and softer material the fracture process will be reverse. Deeper fracture development not only increases machine efficiency it will be very effective in multi bit interaction results in removal of ridges/lands between the groves of the bits, hence reduces specific energy and specific dust provided fracture in each groove is overlapped by adjacent groove [48]. The optimum spacing of the bits/ groves depends on the state of confinement. The state of confinement depends on two cutting parameters 1) depth of adjacent cut 2) The ratio of bit opening to depth of cut. The deeper cut requires deeper impact / more machine force and results in relatively higher/deeper fracture in particular in brittle material. Even though deeper cut require more machine force but the specific energy will be reduced as well as the specific dust. Further deeper cut is an important element in efficient multi bit interaction [48]. Optimization of bit spacing to depth of cut ratio causes fracture in the adjacent groove overlap and the ridge/lands between the groves fails far before the machine cutting force reaches to its maximum value of first cut or adjacent cut too far off from the present cut. In typical cutting process all bits are cutting in the same depth. The effect of their interaction only can be observed when optimum depth of cut is achieved. However if a pre-cut is made then this results in free face [48]. In research carried out indicated, even under smaller rate of cutting advance/less impact, the cutting force in pre-existent two free faces (one on each side of cutting bit, was decreased by 70% than cutting with only one free face) [48]. Taking advantage of free face each bit subsequently cuts towards the free face, therefore the machine cutting force for each individual bit reduced substantially. By reducing the cutting force/communion force, less dust and larger product will be produced [64]. In order to assess the bit spacing, which will produce a clean cut face, bits are tested using one bit at a time at several spacing. Figure 14 shows the sequence in which the cuts are made in the experimental work. At a spacing of 2.0 inch from the edge of the block, First cut to a depth until the bit stuck in the rock was made then the second cut besides the first cut at a bit spacing of 1.0 inch from the first cut has made to a depth until bit stuck in the rock. The depth of the second cut was longer than the first cut. The third cut was made at bit spacing of 1.0 inch, until the bit stuck in

the rock. The length/depth of the third cut was larger than the second cut. These experiments showed that the depth of previous cut increases the depth of subsequent cut. The depth of the third cut is designated as D and fourth, fifth and sixth cuts were made at a bit spacing of D , $1.5D$ and $2D$ inch each cut, the cutting continued until the bit stuck in the rock. The objective of these experiments were to study the effect of precut depth in subsequent cut depth and effects of depth of cut to bit spacing on the depth of subsequent cut.

Figure 14. Experimental pattern.

Experiments were repeated with the above experimental pattern for U76K, new small bit (C), new medium bit (B) and new large bit (A) and the results are summarized as below with the results compared with reference to rate of advance/impact, effect of free face, bit spacing to depth of cut ratio respectively.

17. Experimental Results:

17.1 Effect of Rate of advance/Impact:

The rate of advanced pre-set on the machine at rate of 0.2, 0.3, 0.4, and 0.5 inch/sec. However, the rate of bit penetration/advance into the rock depends on the geometry of the bit and rock resistance to penetration. These two factors affected the penetration rate of the experiments vs. pre-set of rate of advance, because of the limited power of the ARCCS and its elastic structure. In studies associated with comparative analysis of different bit geometry indicated that bit U76K performed better in terms of efficient penetration [65]. Therefore this bit was chosen for the study. Bit U76K has a tip angle of 70 degrees and tip diameter of 9.53 mm, the rate of advance was 0.07 inch/sec. For this experiment when there was no preexisting cuts on its sides, the average penetration force was about 1925 lbf and the cutting force was about 1330 lbf (see figure 15). The final depth of cut achieved was 1.17 inch with 17 revolutions of the drum as shown by 17 points in the figure 15.

Figure 15. Cutting and Penetration forces obtained in U76K during first cut (Rate of advance = 0.07 inch/sec). Final depth of cut was 1.17 inches.

When the rate of advance is increased, many fractures were observed in the rock after the experiment was done, the final depth of cut was measured 1.1 inch on the rock, however on the graph was 0.59 inch achieved at four revolutions of the drum represented by four points in the graph (see figure 16). The average Acoustic Emission (AE) is found to be 17025 counts. The difference between measured depth of cut and recorded data is probably due to dynamic impact and rebound of the LVDT recorded on the chart and

calibration factor of the chart of the chart recorder. Further more, for each experiments the final cutting and penetration forces measured were the last revolution of the drum before the bit stuck to the rock. Hence the depths of cut at that revolution were much less than the last revolution where the bit stuck to the rock.

This proves that energy consumption in the latter was definitely lower than the energy consumption in the former.

Figure 16. Cutting and Penetration forces obtained in increased rate of advance

While comparing the two experiments, it was found that the final depth of cut was a little higher when the rate of advance was 0.07 inch/sec. However this higher depth of cut achieved in 17 cutting revolutions, almost four times more than the revolution of the drum which was setup at 0.14 inch/sec. The average penetration force was found to be 884 lbf and the average cutting force was found to be 341 lbf and the resultant force is found to be 1151 lbf. Specific energy was found to be 23164 lbin/lb and the specific respirable dust was found to be 2.77 mg/lb. This proves that the energy consumption in the latter was definitely lower than the energy consumption in the former. The penetration force and cutting force values for a rate of advance of 0.07 inch/sec are twice as much as the penetration and cutting forces needed for a rate of advance 0.14 inch/sec. This shows that most of the energy was consumed in grinding the rock rather than in cutting.

Experiments were repeated with a higher rate of advance of 0.19 inch/sec with the same bit U76K. when there was no preexisting cuts on its sides, the average penetration force was found to be 729.17 lbf and the average cutting force was found to be 495.8 lbf and the resultant force was found to be 1135 lbf and the Specific energy was found to be 23377 lbin/lb and the specific respirable dust was found to be 1.00 mg/lb. The number of revolutions needed to achieve this final 1.125 inch depth of cut is 5. The average AE count was found to be 25420.

Comparing this experiment with the experiments done before, we can find that the number of revolutions was increased by 1 whereas the final depth of cut is almost twice as obtained in the previous experiment with a rate of advance of 0.14 inch/sec. The specific energy is found to be increased slightly whereas the specific respirable dust is found to be reduced considerably from 2.77 mg/lb when the rate of advance was 0.14 inch/sec to 1 mg/lb when the rate of advance was 0.19 inch/sec. This shows that specific respirable dust decreases when the rate of advance increases and the final depth of cut increases as well. Acoustic Emission (AE) is also found to be increased by 49.3%.

Experiments were repeated with a higher rate of advance of 0.21 inch/sec with the same bit U76K (see figure 17), when there was no preexisting cuts on its sides, the average penetration force was found to be 1184 lbf which is 62% less than the average penetration force used by U76K at a rate of advance of 0.07 inch/sec and the average cutting force was about 565.83 lbf which is 50% less than the average cutting force used by U76K at a rate of advance 0.07 inch/sec and the final depth of cut was found to be 0.625 inches which even though was lower than 1.17 inch final depth of cut achieved with a rate of advance 0.07 inch/sec, the forces used were very low and the number of revolutions to reach this 0.625 inch was 4.

Figure 17. Cutting and Penetration forces obtained in increased rate of advance

The Acoustic Emission (AE) is found to be 25700 counts.

While comparing the rate of advance of 0.21 inch/sec with the rate of advance of 0.14 inch/sec during first cut, it was found that the final depth of cut at a rate of advance of 0.21 inch/sec was 0.625 inch and achieved at 3 revolution cut. A 6% increase in depth of cut with one less cutting revolution. However the penetration and cutting forces were higher 33% and 63% respectively. The Acoustic Emission (AE) is found to be increased by 1%.

17.2 Effect of free face:

From the analytical studies made, effect of free face plays an important role in cutting process. At 0.21 inch/sec rate of advance, utilizing U76K bit during first cut, when there was no preexisting cuts on its sides, the average penetration force was about 1184.17 lbf and the average cutting force was about 565.83 lbf (see figure 18). The final depth of cut was found to be 0.625 inches. The specific respirable dust was found to be 2.98 mg/lb. Following this first cut, a second cut was made at a bit spacing of 1.0 inch and the average cutting and penetration forces were found to be 1176 lbf and 522 lbf respectively. The average cutting and penetration forces are found to be less than the first cut. The final depth of cut was found to be 1.032 inch an increase of 65% and the rate of advance was 0.21 inch/sec. The Acoustic Emission (AE) counts were found to be 21760 counts. The Acoustic Emission (AE) is found to be decreased by 15%.

Figure 18. Cutting and Penetration forces obtained in increased rate of advance

The average resultant force was found to be 1589 lbf. The specific energy was found to be 65631 lbin/lb and specific respirable dust was found to be 2.98 mg/lb. The final depth of cut was found to be 1.032 inches. The final depth of cut is found to increase from 0.625 inches to 1.032 inches when the spacing was increased to 1.0 inch spacing even though the rate of advance was the same. There was no change in the specific respirable dust. When the bit spacing to depth of cut ratio was 1.0 inch, the cutting system worked more efficiently than during the first cut.

Experiments were carried out again with bit spacing of 1.0 inch with a rate of advance of 0.27 inch/sec (see figure 19). The average penetration force and the average cutting force was found to be 1225 lbf and 484 lbf respectively and the average resultant force was 1604 lbf. The final depth of cut was found to be 1.38 inch with 5 revolutions of the drum. The specific energy was found to be 20174 lbin/lb and the specific respirable dust was found to be 0.88 mg/lb. The Acoustic Emission (AE) was found to be 38383 counts.

Figure 19. Penetration, Cutting and Resultant Forces for U76K for 1 inch with a rate of advance was 0.27 inch/sec

Comparing the average penetration and cutting forces, rate of advance of one inch spacing after precut, at 0.21 inch/sec with the rate of advance of 0.27 inch/sec, the final depth of cut was found to be increased from 1.032 inches to 1.38 inches. The number of revolutions of the cutting drum was increase by me. The average penetration and cutting force were found to be 1225 lbf and 484 lbf respectively and resultant force was 1604 lbf. The Acoustic Emission is found to be increased by 44.19%. The penetration force increased slightly by 4%, cutting force decreased by 7.3% and depth of cut increased to 33.7% for the rate of advance of 0.27 inch/sec.

Experiments were carried out again with bit spacing of 1.0 inch with a rate of advance of 0.31 inch/sec (see figure 20). The average penetration force was found to be 1199 lbf and the average cutting force was found to be 503 lbf and the average resultant force was 1595 lbf. The final depth of cut was found to be 1.25 inch with 4 revolutions of the drum. The specific energy was found to be 31423 lbin/lb and the specific respirable dust was found to be 1.56 mg/lb. The Acoustic Emission (AE) is found to be 31375 counts.

Figure 20. Cutting and Penetration forces obtained in increased rate of advance

Comparing the rate of advance of 0.27 inch/sec with a rate of advance of 0.31 inch/sec, it was found that the final depth of cut decreased slightly from 1.38 to 1.25 inches however, the number of revolutions of the cutting drum increased by 1. For 0.31 inch/sec rate of advance, the Penetration force was found to be decreased slightly by 2.1% and the average cutting force was found to be increased by 3.9%, however the resultant force decreased by 0.6%. The specific energy and the specific respirable dust increased by 56% and 77% respectively. The Acoustic Emission (AE) was found to be increased by 22%. The final depth of cut was decreased by 9.4%. However, the final depth of cut for 0.31 inch/sec rate of advance, was achieved by one less drum revolution.

17.3 Effect of Bit Spacing to Depth of cut ratio:

The final depth of cut for the third cut at bit spacing of 1.0 inch was found to be 1.38 inch = 1.0D inch. Experiments were carried out again with bit spacing of 1.38 inch. The average penetration force was found to be 756 lbf and the average cutting force was found to be 385 lbf. The average resultant force was found to be 1064 lbf (see figure 21). The final depth of cut was found to be 1.59 inches. The number of revolutions of the cutting drum was found to be 5. The Specific energy was found to be 11386 lbin/lb and the average specific respirable dust was found to be 0.63 mg/lb. The Acoustic Emission was found to be 49336 counts.

Figure 21. Cutting, penetration and resultant forces using U76K at 1.0D inch (1.38 inch spacing).

Comparing the results for bit spacing of 1.38 inch (bit spacing to depth of cut ratio of 1.0), at bit spacing of 1.0 inch, it was shown that the final depth of cut obtained for 1.38 inch bit spacing was 0.2 inch more than the one obtained in the 1.0 inch bit spacing. The cutting force at the 1.38 inch spacing was 25% less than the cutting force at 1.0 inch bit spacing and the penetration force at 1.38 inch bit spacing was 15% less than the penetration force for 1.0 inch bit spacing. Thus increasing depth of precut/free face increases the depth of adjacent cut and reduces the forces. The Acoustic Emission is found to be increased by 28.5%.

Experiments were repeated with bit spacing equal to 1.5D ($1.5 \times 1.38 = 2.07$ inch) spacing (see figure 22). The average resultant force was found to be 1276 lbf. The average cutting force was found to be 433 lbf and the average penetration force was found to be 931.8 lbf. The actual depth of cut was found to be 1.5 inch. The number of revolutions of the cutting drum is found to be 4. The specific energy was found to be 9251 lbin/lb and the specific respirable dust was found to be 0.54 mg/lb. The Acoustic Emission (AE) is found to be 24875 counts.

Figure 22. Cutting, penetration and resultant forces using U76K at 1.5D inch (2.07 inch spacing).

Comparing 2.07 inch spacing with 1.38 inch bit spacing, there was difference between the two both with reference to cutting, penetration, resultant forces and dust generation as well as depth of cut. Even though there was a reduction in specific respirable dust from 0.63 mg/lb to 0.54 mg/lb and reduction in specific energy from 11386 lbf to 9251 lbf, the final depth of cut is found to be decreased from 1.59 to 1.5 inches. By increasing bit spacing to depth of cut, forces and respirable dust increased and the depth of final cut decreased. Acoustic Emission is found to be decreased by 49.5%.

Experiments were carried out with bit spacing 2D inch spacing with $2D = 2 \times 1.38 = 2.76$ inch spacing (see figure 23). The average resultant force was found to be 1248 lbf. The average cutting and penetration force was found to be 378 lbf and 952 lbf respectively. The final depth of cut was found to be 1.3 inch. The number of revolutions of the cutting drum was found to be 5. The specific energy was found to be 23072 lbin/lb and the specific respirable dust was found to be 1.38 mg/lb. The Acoustic Emission (AE) is found to be 16,620 counts.

Figure 23. Cutting, Penetration and Resultant Forces using U76K at 2D inch (2.76 inch) spacing.

The results obtained for bit spacing to depth of cut ratio (2D inch spacing) were compared with 1.5D inch spacing. The value of specific respirable dust is found to increase twice for 2D inch than 1.5D inch spacing. The specific energy is found to increase twice in 2D inch spacing than for 1.5D inch spacing. The final depth of cut is found to decrease from 1.5 to 1.3 inch. The number of revolutions of the cutting drum was found to increase from 4 to 5. The Acoustic Emission is found to be decreased by 33.18%. Thus optimum values of free face and bit spacing to depth of cut ratio together increase the efficiency of the cutting system.

17.4 Experiments carried out with different bit geometry:

Three new bits were designed by Khair, Project Investigator. The experiments on this new bit were carried out under the same testing conditions. The bits are named as small (C), medium bit (B) and large (A) bit accordingly.

Figure 24. Small new bit (C) used in the experiments.

17.5 Experiments with small new bit (C):

Experiments were repeated with small new bit (C) in first cut (see figure 24). The average penetration force was found to be 1907.5 and the average cutting force was found to be 822.5 lbf. The average resultant force was found to be 2557.72 lbf. The final depth of cut was found to be 0.8 inches. The number of revolutions of the cutting drum was found to be 2. The specific energy was found to be 57937 lbin/lb. The specific respirable dust was found to be 4.46 mg/lb. The Acoustic Emission was found to be 17,700 counts. Comparing the first cut value obtained using the new small bit (C) with first cut obtained in U76K the number of revolutions needed to achieve a final depth of cut of 0.8 inches is

2.

Figure 25. Shows the Cutting, Penetration and Resultant Forces using small new bit (C) in first cut.

The specific dust generation is found to increase (4.46 mg/lb) in new small bit (C) as first cut is not the optimum parameter for the new small bit (C). The average resultant force is found to decrease from 3016 lbf to 2556 lbf when comparing the resultant force obtained with first cut using U76K utilizing 14 revolutions with resultant force obtained

using new small bit (C) utilizing in 2 revolutions.

Experiments were repeated with 1.0D inch spacing where the value of 1.0D = 0.8 inch spacing (see figure 26). Experiments were repeated utilizing new small bit (C). The average penetration force was found to be 1382.5 lbf, the average cutting force was found to be 507.5 lbf. The average resultant force was found to be 1778.03 lbf. The final depth of cut was found to be 1.125 inches. The specific energy is found to be 19096 lbf and the specific respirable dust is found to be 1.94 mg/lb. The number of revolutions of the cutting drum is found to be 2. The Acoustic Emission (AE) is found to be 34,200 counts.

When comparing the experiments conducted with new small bit (C) in first cut with experiments conducted with 1.0D inch spacing, the rate of advance is found to increase from 0.8 to 1.125 inch and the specific respirable dust is found to decrease from 4.46 to 1.94 mg/lb where as the number of revolutions of the cutting drum remains the same. The specific energy in 1.0D inch is found to be decrease by 3 times compared to the specific energy obtained in first cut. The Acoustic Emission is found to increase nearly twice the number of counts obtained in first cut.

Figure 26. Cutting, Penetration and Resultant Forces using new small bit (C) in 1.0D inch spacing.

Experiments were repeated with 1.5D inch ($1.5 \times 0.8 = 1.2$ inch) spacing (see figure 27). The average penetration force was found to be 1907.5 lbf, the average cutting force was found to be 805 lbf. The resultant force was found to be 2541 lbf. The final depth of cut was found to be 1.4 inches. The number of revolutions of the cutting drum was found to be 2. The Specific energy was found to be 14875 lbf and the specific respirable dust was found to be 1.14 mg/lb. The Acoustic Emission (AE) is found to be 47,950 counts.

Comparing the results obtained in 1.5D inch spacing with the results obtained in 1.0D inch spacing, it was found that the final depth of cut is increased to 1.4 inch, and the number of revolutions remains the same. The specific respirable dust is found to decrease from 1.94 mg/lb in 1.0D inch spacing to 1.14 mg/lb in 1.5D inch spacing. The resultant forces were found to be increased nearly 70%. The specific energy is found to decrease by 28% in 1.5D inch spacing compared to 1.0D inch spacing. The Acoustic Emission is found to increase by 40%.

Comparing the results obtained in 1.5D inch spacing with the results obtained in first cut (1.0D) it was found that the final depth of cut is to be increased from 0.8 to 1.4 inch (an increase of 75%). The respirable dust is found to be decrease from 4.46 mg/lb to 1.14 mg/lb. The number of revolutions of the drum remains the same. The specific energy is found to be decreased by nearly 4 times (57937 lbin/lb to 14875 lbin/lb). The Acoustic Emission is found to increase by nearly 3 times from 17,700 counts to 47,950 counts.

Figure 27. Cutting, Penetration and Resultant Forces using new small bit (C) in 1.5D inch spacing.

Experiments were repeated with 2D inch spacing (see figure 28). The average penetration force is found to be 1102.5 lbf. The average cutting force is found to be 389.375 lbf. The

average resultant force is found to be 1405.89 lbf. The final depth of cut was found to be

Figure 28. Cutting, penetration and resultant forces in new small bit (C) at 2D inch spacing.

1.2 inches. The specific energy is found to be 5284 lbin/lb and the specific respirable dust is found to be 0.46 mg/lb. The Acoustic Emission is found to be 23,350 counts.

Comparing the experiments done with 1.5D inch spacing with the experiments done with 2D inch spacing, it was found out that the final depth of cut decreased from 1.4 inch to 1.2 inch and the number of revolutions of the cutting drum also gets increased from 2 to 4. Eventhough there is a decrease in the depth of cut, the specific respirable dust increased by more than twice compared to experiments done with 1.5D inch spacing. The Specific energy is found to be decreased by three times (from 14875 lbin/lb in 1.5D inch spacing to 5284 lbin/lb in 2D inch spacing). The Acoustic Emission (AE) is found to decrease by 50%.

17.6 Experiments done with new design medium bit (B):

Experiments were repeated with new design medium bit (B) as shown in figure 29.

Figure 29. Medium new bit (B) used in the experiments.

Experiments were repeated with new medium bit (B) with first cut (see figure 30). The average penetration, cutting and resultant forces were found to be 994 lbf, 469 lbf and 1711 lbf respectively. The final depth of cut was found to be 1.2 inches. The number of revolutions of the cutting drum is 5. The rate of advance is 0.24 inch/sec. The specific respirable dust is found to be 2.15 mg/lb. The specific energy is found to be 49474 lbin/lb. The Acoustic Emission is found to be 19800 counts.

Comparing the first cut experiments of new medium bit (B) with new small bit (C) it was observed that the resultant force utilized by new medium bit (B) during first cut is found to be 49% less.

Figure 30. Cutting, Penetration and Resultant Forces in new medium bit (B) used in the experiments in first cut.

than the resultant force utilized by new small bit (C). Eventhough the number of cutting revolutions of the drum has increased from 2 to 5 the specific respirable dust is found to be decreased by 50% (from 4.46 mg/lb to 2.15 mg/lb). The final depth of cut is found to be increased from 0.8 inch in new small bit (C) to 1.2 inch in new medium bit (B). The

specific energy is found to be decreased by 17%. The Acoustic Emission is found to be increased by 12%.

Experiments were done with new medium bit (B) using 1.0D inch spacing where $D = 1.2$ inch spacing (see figure 31).

Figure 31. Cutting, penetration and resultant forces in new medium bit (B)

The average penetration, cutting and resultant forces were found to be 639 lbf, 385 lbf and 867 lbf. The final depth of cut was found to be 1.28 inch. The specific respirable dust was found to be 1.13 mg/lb. The specific energy is found to be 1623 lbin/lb. The number of revolutions of the cutting drum was found to be 3. The Acoustic Emission (AE) is found to be 24,400 counts.

Comparing experiments done using medium bit with first cut and with 1.0D inch spacing, it was observed that the resultant force was found to be decreased by half and the final depth of cut was increased from 1.2 inch to 1.28 inch (an increase of 6.7%). The number of revolutions of the cutting drum is found to be decreased from 5 to 3. The specific respirable dust is found to be decreased from 2.15 mg/lb to 1.13 mg/lb (a decrease of 90%). The specific energy is found to be decreased from 49474 lbin/lb to 1623 lbin/lb. The Acoustic Emission (AE) is found to be increased by 23.2%

Experiments were done using new medium bit (B) using 1.5D inch spacing = $1.5 \times 1.2 = 1.8$ inch spacing (see figure 32).

Figure 32. Cutting, penetration and resultant forces in new medium bit (B)

The average penetration, cutting and resultant forces were found to be 1178 lbf, 542 lbf and 1608 lbf. The final depth of cut was found to be 1.47 inch. The specific respirable dust was found to be 2.23 mg/lb. The specific energy is found to be 48443 lbin/lb. The number of revolutions of the cutting drum was found to be 6. The Acoustic Emission (AE) is found to be 17667 counts.

Comparing the experiment results with 1.0D inch and 1.5 D inch spacing, the resultant force is found to be increased by twice. The number of revolutions of the cutting drum is found to be increased twice from 3 to 6 in 1.5D inch spacing. The final depth of cut was found to be increased from 1.28 inch to 1.47 inch (an increase of 15%). The Specific respirable dust is found to be increased from 1.13 mg/lb to 2.23 mg/lb (an increase of 97%). The Specific energy is found to be increased from 1623 lbin/lb to 48443 lbin/lb. The Acoustic Emission (AE) is found to be decreased by 27.6%.

Experiments were conducted using new medium bit (B) with a spacing of 2D inch where D is equal to 1.2 inch and the value of 2D is 2.4 inch (see figure 33).

Figure 33. Cutting, Penetration and Resultant Forces using new medium bit (B) with 2D inch spacing (2.4 inch).

The average penetration, cutting and resultant forces were found to be 851 lbf, 303 lbf and 1087 lbf. The final depth of cut was found to be 0.5 inch. The specific respirable dust was found to be 0.27 mg/lb. The specific energy is found to be 353 lbin/lb. The resultant force was found to be 1087 lbf. The number of revolutions of the cutting drum was found to be 3. The Acoustic Emission (AE) is found to be 5967 counts.

Comparing the experiments done with 2D inch spacing with 1.5D inch spacing, we find eventhough the resultant force is found to be decreased by 32%, the depth of cut is found to be decreased by 33% of the depth of cut of 1.47 inches obtained in 1.5D inch spacing. The number of revolutions was found to be decreased by 50%. The specific respirable dust is found to be 7 times lesser than in 1.5D inch spacing. The specific energy is found to be decreased from 48443 lbin/lb to 353 lbin/lb. The Acoustic Emission is found to be decreased by nearly 3 times from 17667 counts to 5967 counts.

17.7 Experiments done using new large bit (A):

Experiments were done using new large bit (A) with same set of experiments using the same experimental procedure. The new large bit (A) used in the experiments is as shown in figure 34.

Figure 34. Shows the new large bit (A) used in the experiment.

Experiments were repeated with new large bit (A) with first cut (see figure 35). The average penetration, cutting and resultant forces were found to be 980 lbf, 443 lbf and 1332 lbf respectively. The final depth of cut was found to be 1.5 inches. The number of revolutions of the cutting drum is 6. The rate of advance is 0.25 inch/sec. The specific respirable dust is found to be 0.29 mg/lb. The specific energy is found to be 6618 lbin/lb. The Acoustic Emission (AE) is found to be 41550 counts.

Comparing the first cut experiments of new large bit (A) with new medium bit (B) and new small bit (C) we find that the resultant force is found to be decreased from 2556 lbf in small bit (C) to 1711 lbf in medium bit to 1332 lbf in large bit during first cut. The final depth of cut was found to be increased from 0.8 inch to 1.2 inch to 1.5 inch in large bit. The specific respirable dust was found to be 4.46 mg/lb to 2.15 mg/lb in medium bit to 0.29 mg/lb in large bit.

Figure 35. Cutting, Penetration and Resultant Forces using new large bit (A) during first cut.

The number of revolutions of the cutting drum is found to be increased by 2 to 5 in medium bit to 6 in large bit even though the specific respirable dust is found to decrease and the resultant force is found to decrease. The specific energy is found to be decreased

from 57937 lbin/lb in new design small bit (C) to 49474 lbin/lb in new design medium bit (B) to 6618 lbin/lb in new design large bit (A). The Acoustic Emission is found to be increased by 11.9% in new design small bit (C) when compared with new design medium bit (B) and found to be increased by 2 times from 19,800 counts to 41,550 counts when compared with new design large bit (A).

Experiments were repeated using large bit with 1.0D inch spacing where the value of D = 1.5 inch spacing (see figure 36).

Figure 36. Cutting, Penetration and Resultant Forces using new large bit (A) with 1.0D inch spacing (1.5 inch).

The average penetration, cutting and resultant forces were found to be 1213 lbf, 490 lbf and 1597 lbf. The final depth of cut was found to be 1.375 inch. The specific respirable dust was found to be 0.66 mg/lb. The resultant force was found to be 1597 lbf. The number of revolutions of the cutting drum was found to be 3. The specific energy is found to be 10497 lbin/lb. The Acoustic Emission is found to be 44,533 counts.

Comparing experiments done using large bit with first cut and with 1.0D inch spacing, we find that the final depth of cut increased from 1.5 inch to 1.375 inch. The specific respirable dust is found to be increased from 0.29 to 0.66 mg/lb. The resultant force is found to be increased from 1332 lbf to 1597 lbf in 1.0D inch spacing (an increase of 1.5%). The specific energy is found to be increased from 6618 lbin/lb to 10497 lbin/lb (an increase of 59%). The Acoustic Emission is found to be increased by 82.5%.

Experiments were repeated with new large bit (A) using 1.5D inch spacing (1.5 x 1.5 = 2.25 inch) see figure 37.

Figure 37. Cutting, Penetration and Resultant Forces using new large bit (A) with 1.5 D inch spacing (2.25 inch).

The average penetration, cutting and resultant forces were found to be 932 lbf, 433 lbf and 1275 lbf. The final depth of cut was found to be 1.5 inch. The specific respirable dust was found to be 2.06 mg/lb. The specific energy was found to be 33950 lbin/lb. The number of revolutions of the cutting drum was found to be 4. The Acoustic Emission (AE) is found to be 49,350 counts.

Comparing the results obtained in 1.0D inch spacing with 1.5D inch spacing, the final depth of cut is found to be increased from 1.375 to 1.5 inch. (an increase of 9%). The specific respirable dust is found to be increased by 68% from 0.66 mg/lb in 1.0D inch spacing to 2.06 mg/lb in 1.5D inch spacing. The number of revolutions is found to increase from 3 to 4 an increase of one revolution. The specific energy is found to be increased by 3 times from 10497 lbin/lb in 1.0D inch spacing to 33950 lbin/lb in 1.5D inch spacing. The Acoustic Emission is found to be increased by 11%.

Experiments were conducted using new large bit (A) with 2D inch spacing (3 inch spacing) (see figure 38).

Figure 38. Cutting, Penetration and Resultant Forces using new large bit (A) with 2 D inch spacing (3 inch).

The average penetration, cutting and resultant forces were found to be 892.5 lbf, 350 lbf and 1167 lbf. The final depth of cut was found to be 0.8 inch. The specific respirable dust was found to be 0.49 mg/lb. The specific energy is found to be 7032 lbin/lb. The number of revolutions of the cutting drum was found to be 3. The Acoustic Emission (AE) is found to be 44,700 counts.

Comparing the experiments done with 2D inch spacing with 1.5D inch spacing, we find that the resultant force decreases from 1275 lbf to 1167 lbf (a decrease of 9.2%). The number of revolutions of the cutting drum is found to be decreased from 4 to 3. The final depth of cut is found to be decreased from 1.5 to 0.8 inch. (an increase almost half of the value). The specific respirable dust is found to be decreased from 2.06 mg/lb to 0.49 mg/lb. The specific energy is found to be decreased from 33950 lbf to 7032 lbf. The Acoustic Emission is found to be decreased by 9.4%.

18. ANALYSIS UTILIZING U76K BIT

18.1 Effect of Rate of advance (First cut):

Specific energy is defined as the work done by cutting and penetration forces per unit of material being cut. Specific respirable dust is defined as the weight of respirable dust generated per unit weight of material being cut.

While comparing the experiments done with 0.07 inch/sec rate of advance and 0.14 inch/sec rate of advance in first cut, it was found that the final depth of cut was a little higher than when the rate of advance was 0.07 inch/sec (0.178 cm/sec). However, this higher depth of cut achieved in 17 cutting revolutions is almost four times more than the rate of advance was 0.14 inch/sec (0.36 cm/sec). This proves that the energy consumption for 17 cutting revolutions in the latter was definitely lower than the energy consumption for in the former. The penetration and cutting force values for a rate of advance of 0.07 inch/sec (0.18 cm/sec) are twice and four times than the rate of advance 0.14 inch/sec (0.36 cm/sec) respectively. This shows that most of the energy for 0.07 inch/sec (0.18 cm/sec) rate of advance, was consumed in grinding the rock rather than in cutting. While comparing the rate of advance of 0.21 inch/sec (0.53 cm/sec) with a rate of advance of 0.14 inch/sec (0.36 cm/sec) during first cut, it was found that the final depth of cut at a rate of advance of 0.21 inch/sec (0.53 cm/sec) was 0.625 inches (1.59 cm) and achieved at three revolutions. A 6% increase in depth of cut with one cutting revolution however the penetration and cutting forces were higher 33% and 63% respectively. This increase of cutting, penetration is due to increase in fracture intensity of the rock. This is also proved by the increase in the Acoustic Emission Counts in 0.21 inch/sec rate of advance by 50% when compared with Acoustic Emission in 0.14 inch/sec rate of advance.

Figure 39. Comparison between rate of advance and specific energy consumed in U76K

Comparing the specific energy obtained in U76K with the rate of advance of 0.14 inch/sec and a rate of advance of 0.21 inch/sec, it can be found that there is an increase in specific energy by 56% and a slight increase in specific dust by 7% as shown in the figures 39 & 40.

Figure 40. Comparison between rate of advance and specific respirable dust in mg/lb in U76K in first cut.

Acoustic Emission is found to be increased by 51% when comparing rate of advance (0.14 inch/sec) with AE obtained with rate of advance of 0.21 inch/sec as shown in figure 41.

Figure 41. Comparison between rate of advance and Acoustic Emission (AE) counts in U76K during first cut.

18.2 Effect of Rate of Advance during Subsequent Cuts (1.0 inch spacing):

Figures 42 & 43 indicate that both the specific energy and the specific dust decrease slightly as the rate of advance increasing from 0.19 to 0.31 in/sec.

Figure 42. Comparison between rate of advance and specific energy consumed in U76K in 1.0 inch spacing

Figure 43. Comparison between the rate of advance vs. specific respirable dust in mg/lb in U76K in 1.0 inch spacing

Figure 44. Comparison between rate of advance vs. Acoustic Emission in counts in U76K in 1.0 inch spacing

Figure 44 indicates that Acoustic Emission (AE) is found to be decreased by 14.4% from a rate of advance of 0.19 inch/sec to 0.21 inch/sec and found to be increased by 44% from a rate of advance of 0.21 inch/sec to 0.31 inch/sec. Acoustic Emission is found to be increased with rate of advance in 1.0 inch spacing.

18.3 Effect of depth of cut/free face:

As the depth of free face increases the depth of subsequent cut increases and specific energy and specific respirable dust decreases. From figure 45 we can find that the depth

of free face increases the depth of subsequent cuts increases from 0.59 inches in first cut to 1.032 inches in 1.0 inch spacing to 1.125 inch spacing in the subsequent 1.0 inch spacing and the specific respirable dust decreased from 2.77 mg/lb to 1.00 mg/lb respectively.

Figure 45. Depth of free face vs. depth of subsequent cuts in inches.

18.4 Effect of S:D ratio:

As the ratio of bit spacing to depth of cut ratio increases, the depth of cut decreases and specific energy and specific respirable dust increases as shown in figure 46 and 47.

Figure 46. Spacing in inches vs. Specific energy in lbin/lb

From the figure 46 we can find that as the S:D ratio increases the specific energy increases and figure 47 shows the specific respirable dust increases too when depth of cut decreases from 1.59 to 1.5 and to 1.3 respectively.

Figure 47. Spacing in inches (various S:D ratios) vs. specific respirable dust in mg/lb

From the figure 48 we can find that as the S:D ratio increases the Acoustic Emission decreases from 49,336 counts to 24,875 counts to 16,620 counts respectively

Figure 48. Spacing in inches (various S:D ratios) vs. AE Counts

19. ANALYSIS UTILIZING NEW BITS

19.1 Effect of Rate of advance (First cut)

While comparing the experiments done with new small (C), medium (B) and large (A) bits, in first cut with the specific energy consumed (see figure 49)

Figure 49. Comparison between rate of advance and specific energy consumed in new bit.

While comparing the experiments done with new small (C), medium (B) and large (A) bits during first cut we find that the specific energy increases with rate of advance. The number of revolutions increases from 2 with a rate of advance of 0.4 inch/sec to 5 with a rate of advance of 0.24 inch/sec to 6 with a rate of advance of 0.25 inch/sec

Figure 50. Comparison between rate of advance in inch/sec vs specific respirable dust in mg/lb in new bit in first cut.

Figure 51. Comparison between rate of advance in inch/sec vs Acoustic Emission (AE) in counts in new bit in first cut.

While comparing the experiments done with new small (C), medium (B) and large (A) bits during first cut we find that the Acoustic Emission (AE) decreases with rate of advance as shown in figure 51.

19.2 Effect of rate of advance during subsequent cut (1.0D inch spacing):

Figures 52 and 53 indicated that both the specific energy and specific respirable dust. As the rate of advance increases in subsequent cuts the specific energy and specific respirable dust increases as shown in the figure.

Figure 52. Comparison between rate of advance and specific energy in new bit in subsequent cut.

Figure 53. Comparison between rate of advance and specific respirable dust in new bit in subsequent cut

Figure 54. Comparison between rate of advance and AE counts in new bit in subsequent cut.

Figure 54 indicates that as the rate of advance increases Acoustic Emission (AE) counts increases.

19.3 Effect of depth of cut/free face:

As the depth of free face increases the depth of subsequent cut increases in new small bit (C) from 0.8 inches to 1.125 inches, 1.4 inches, and decreases to 1.2 inches in subsequent cut at 2D inch spacing.

Figure 55. Depth of cut vs depth of subsequent in inches in new small bit (C)

In new medium bit (B), the depth of free face increases as depth of subsequent cut increases from 1.2 to 1.28 and 1.47 inches respectively and then decreases to 0.5 inches in 2D inch spacing.

Figure 56. Depth of cut vs depth of subsequent in inches in new medium bit (B)

In new large bit (A), as the depth of free face increases from 1.375 to 1.5 inches and then decreases to 0.8 inches in 2D inches.

Figure 57. Depth of free face vs depth of subsequent cuts in inches.

19.4 Effect of S:D ratio :

19.4.1 Effect of S:D ratio in new small bit (C):

As the ratio of bit spacing to depth of cut ratio increases the specific energy decreases as shown in the figure 58 for new small bit (C).

Figure 58. Spacing in inches vs specific energy in lbin/lb in new small bit (C)

From figure 59, we find that the specific respirable dust decreases as the ratio of bit spacing to depth of cut ratio increases in new small bit (C).

Figure 59. Spacing in inches vs specific respirable dust in mg/lb for new small bit (C)

Figure 60. Spacing in inches vs Acoustic Emission in Counts for new small bit (C)

From figure 60, we find that the acoustic emission decreases as the ratio of bit spacing to depth of cut ratio increases in new small bit (C).

19.4.2 Effect of S:D ratio in new medium bit (B):

As the ratio of bit spacing to depth of cut ratio increases the specific energy increases first increases and then decreases as shown in the figure 61.

Figure 61. Spacing in inches vs specific energy in lbin/lb for new medium bit (B)

As the ratio of bit spacing to depth of cut ratio increases, we find that the specific respirable dust increases in 1.5D inch and then decreases in 2D inch spacing in new medium bit (B) as shown in figure 58. As the ratio of bit spacing to depth of cut ratio increases, we find that the Acoustic Emission (AE) decreases in both 1.5 inch spacing and 2D inch spacing.

Figure 62. Spacing in inches vs specific respirable dust in mg/lb in new medium bit (B).

Figure 63. Spacing in inches vs AE Counts in new medium bit (B).

19.4.3 Effect of S:D ratio in new large bit (A):

As the ratio of bit spacing to depth of cut ratio increases the specific energy increases at 1.5D inch spacing and decreases at 2D inch spacing for new large bit (A) as shown in figure 64.

As the ratio of bit spacing to depth of cut ratio increases the specific respirable dust increases at 1.5D inch spacing and decreases at 2D inch spacing for new large bit (A) as shown in figure 65.

Figure 64. Spacing in inches vs specific energy in lbin/lb in new large bit (A).

Figure 65. Spacing in inches vs specific respirable dust in mg/lb in new large bit. (A)

As the ratio of bit spacing to depth of cut ratio increases the Acoustic Emission increases at first cut from 41550 counts to 44533 counts at D inch spacing and to 49350 counts at 1.5D inch spacing and decreases to 44700 counts at 2D inch spacing for new large bit (A) as shown in figure 66.

Figure 66. Spacing in inches vs AE Counts in new large bit. (A)

20. CONCLUSION:

Efficient utilization of continuous miner cutting head requires optimization of cutting tool, and drum geometry, understanding of fracture mechanisms associated with cutting material and constructing cutting tools ideal for the type of material to be cut. Higher rate of advance increases fracture intensity around the tool –rock interface and assist removal of the ridges/land in multiple bit interaction, provided optimum bit spacing to depth of cut is maintained in the cutting process. Optimum values of free face and bit spacing to depth of cut ratio together increase the efficiency of the cutting system. As the depth of free face increases the depth of subsequent cut increases.

There are some impertinent conclusions reached from this study which are summarized as follows:

- The blunt bit will generate more dust and less efficiency in terms of providing optimum depth
- The most favorable profile angle of bit is about 80°.
- The optimal depth of cut is depending on the geometry of the bit and material properties to be cut for specific machine force.
- Profile angle of the bit body should be less than the profile angle of the bit tip for efficient bit penetration and machine efficiency.
- Higher rate of advance/dynamic impact increases fracture intensity around the tool-rock interface and assist removal of the ridges/ land in multiple bit interaction provided optimum bit spacing to depth of cut ratio is maintained in the cutting process.
- The optimum ratio of bit spacing to depth of cut ratio depends on optimum depth of cut, bit geometry and brittle-ductile characteristics of cutting material. A ratio of 2.0-3.0 for rock is recommendable.
- Free Face is important in coal/rock cutting to reduce dust generation and increase cutting efficiency.
- New design small bit (C) is found to be more efficient than new design medium bit.
- New design small bit (C) is found to perform better in 1.5D inch spacing (2.4 inch) with higher final depth of cut even though specific respirable dust and

specific energy is found to be increased and Acoustic Emission is found to be decreased.

- New design medium bit (B) is found to perform better in 2D inch spacing (1.6 inch) spacing in terms of specific respirable dust, depth of cut and specific energy.
- New design large bit (A) is found to produce minimum dust and maximum depth of cut and minimum specific energy and maximum Acoustic Emission (AE) counts and is the most efficient among the new bits.
- New design medium bit (B) is found to be more efficient than new design small bit (C).
- Optimum values of free face and bit spacing to depth of cut ratio of the new bits increases the efficiency of the cutting system.

21. RECOMMENDATION FOR FUTURE RESEARCH:

Research can be further enhanced by studying multiple bit interaction in the new bits as only individual bits are tested in the current research. The reason can also be extended by studying multiple bit interactions in faster rate of advance of the cutting drum. Further research can also be conducted on effective land/ridge removal by increasing the efficiency of the continuous miner's cutting head.

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