PERFORMANCE PREDICTION
OF CONTINUOUS SURFACE MINERS
FROM GEOPHYSICAL LOGS

by
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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Mining Engineering).

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ABSTRACT

The primary goal of this study was to investigate the feasibility of predicting the performance of a continuous surface miner from the geophysical logs obtained from a surface coal mining operation.

An intensive regression analysis was carried out to develop the relationship between the specific energy of cutting, the material physical properties and the geophysical logs both in the overburden and the coal. The best correlations were obtained between the specific energy, uniaxial compressive strength and the apparent density. A regression model was then developed to allow prediction of machine production rates from the apparent density measured in geophysical logging.

An economic analysis was performed to determine the potential savings in mining costs by using the continuous mining system as opposed to the current truck and shovel operation as employed at the mine. The results showed potential cost savings on the order of $0.17 to $0.23 by using the continuous surface miner in conjunction with conveyor belt haulage. Additional reductions in continuous mining costs appeared possible by optimizing the machine design by
changes in bit design and the drum lacing pattern.
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DEDICATIONS

For Bruce, for always.
ACKNOWLEDGEMENTS

A lot of people were instrumental in helping me to complete this thesis, and I would like to take this opportunity to acknowledge them and thank them for their assistance:

The Carter Mining Company in Gillette, Wyoming, particularly Mr. Marc Lemieux, for his insight, energy and enthusiasm.

My Advisor, Dr. Levent Ozdemir, for his continual support and advice.

Krupp Industrietechnik GMBH, Herr Dr. Kris Neimann-Delius and Herr Witnauer of Duisberg, FDR; and Steve Burgess of McNally-Rand, Pittsburgh, all of whom generously allowed me access to considerable quantities of necessary material for the completion of this project.

Members of the faculty of the Mining Department at the Colorado School of Mines, and to my family and friends in Scotland who supported and encouraged me. And not least to all my friends at the Henderson Mine, in particular Jeff Kobie, for their inspiration. Thank you all.

And finally, to the late Bruce Eric Carlson of Idaho Springs whose strength, bravery, and tenacity stand as a
rare and shining example forever to all men; thank you for giving me the courage and conviction to go on.
CHAPTER 1

INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

The primary purpose of this study is to examine the suitability of material at a surface coal mining operation in the Powder River Basin, Wyoming, for mechanical excavation by a surface continuous miner.

This assessment is made by implementing a model in which a regression analysis technique relates the variables that describe certain characteristics of the material and evaluates the effectiveness of the model.

The overall goals and objectives of this study are discussed in greater detail in the following chapter, but it is important not to lose sight of the original intent to develop a model of the deposit that can be used to model the productivity and operating costs of a Continuous Surface Miner excavating coal and/or overburden, specifically to be able to identify on a reasonable scale sandstone lenses that are between 18" and 2 $\frac{1}{2}$' to 3' thick.
1.1.1 Introduction. The domestic surface coal mining industry, in the United States and other historically significant producing countries, faces increasingly stiff competition from developing nations around the world; of particular importance are China, which has tremendous untapped reserves, the USSR and certain Eastern Bloc countries. The latter, particularly in the light of low labor overheads and the recent removal of economic and political restrictions, may pose a special potential threat also to coal producers in the United States.

This and other factors, particularly socio-economic constraints resulting from legislation, and increasing transport costs, have required major US producers to produce coal more efficiently and economically than their predecessors did.

This in turn has led to move available research dollars in order to improve the efficiency of current mining systems; the result has been an irregular but general increase in equipment size with a corresponding productivity increase that is not necessarily proportionate or a linear
function. Coincident with this has been the increase in the development of innovative mining systems that provide alternative methods of removing coal and overburden.

Innovative mining systems have traditionally found it difficult to break new ground. Put more simply, whilst there is an obvious need for new ideas in mining, there is a strong prejudice against major changes in current systems.

This attitude of "if it ain't broke, don't fix it", has essentially stifled growth of new technology. However, recent trends in the mining industry, particularly legislative attempts to reduce the amount of sulfur dioxide emissions produced by coal-fired power stations, have forced many of the major coal-producers to re-think their mining strategy.

Nowhere has this been more evident than in the large surface coal mining operations in the American West and Mid-West. More specifically, in the Powder River Basin where, almost 15 per cent of the nation's coal is mined, producers have found more than just their profit margins threatened. Increasing transport costs which comprise some 40 to 50 per
cent of the overall costs, the need to redefine available reserves and to change blending programs because of low sulfur stipulations on coal contracts, have meant that the need to reduce costs is in some cases critical.

It could also be theoretically argued that as Eastern and mid-West producers feel the need to close or face severe restrictions because they produce higher sulphur coal, Western producers, such as those in the Powder River Basin, are given an incentive to increase their production to meet demands.

With the advent of innovative mining systems such as in-pit crushing, not an entirely new concept in itself, and high angle conveyors, both the mining companies and the mining equipment manufacturers realized the need to expand their field of view to include the underground mining environment in their research for a more efficient surface mining method.

This itself was not an entirely new concept either, but it isolated and identified a significant inefficiency in the
system. This was identified as being the cyclic nature of the present system.

By this time the impact of continuous mining in underground coal mines, particularly the longwall, was just being realized. In particular the cutting mechanism of continuous miners was being analyzed, particularly in South African coal mines in the early 1970’s, at a time when the impact of mechanical excavation on rock excavation processes was just being realized (Roxborough 1985).

Adapting a longwall to a surface coal mining operation and environment has not been considered feasible, though it has previously been examined. What did show enormous potential in terms of adaption is the continuous miner; hence the conception of the Continuous Surface Miner. This type of technology was developed initially as a result of the adaption of pavement profiling equipment to the surface mining industry. This resulted in a continuous miner for surface mining applications that could mine selectively both thick and thin seams. The original technology utilized a mandrill or cutting drum located underneath the machine;
this arrangement became modified so that the drum became mounted on the front of the miner, precipitating easier access to tools for changing, maintenance and improved cutting ability. Since this initial research was begun the development of this surface mining technology has been acquired by Krupp Industrietechnik GmbH in West Germany.

The goal was to produce a piece of mining and excavating coal and overburden in a continuous fashion. Mechanized excavation since the mid 1960’s has progressively been viewed as a serious and attractive alternative to the older cyclic mining methods; however there were a number of problems. Firstly the niche for mechanized excavation systems in a surface mining environment was occupied by the Bucket Wheel Excavator, which although efficient in the right applications, was nevertheless not very flexible and required a large, sometimes prohibitive initial investment.

Secondly, mechanized excavation systems had been traditionally restricted to mining in softer, unconsolidated deposits of low compressive and tensile strength that required no prior preparation in the form of blasting. It
was also considered advantageous if these seams were fairly homogenous and continuous in nature.

These two problems were offset by the obvious advantages that mechanized excavation systems had to offer; with increased research into pick manufacture and excavation systems it was soon realized that these machines were becomingly increasingly suitable for the excavation of moderate or higher strength materials. Another major selling point was the ease with which they apparently lent themselves to automation and ultimately robotic control.

Additional advantages of continuous mechanical excavation systems were the ability to mine selectively thin, undulating seams and the ability to do so and load in a continuous fashion. Lower overheads meant improved economic viability and the flexibility and versatility of the system meant that it could be used either with the conventional truck haulage system already in place at the mine or continuous haulage such as mobile in-pit conveyor systems.
A primary advantage is the elimination of drilling and blasting costs and the significant reduction in the costs of primary crushing due to reduced requirements; these two areas alone can be identified as significant cost savers.

Finally, the machine productivity in continuous surface mining could not be matched using conventional methods, under specific conditions. This is principally due to the ability of the equipment to be able to mine material while eliminating a prohibitive portion of the mining costs directly attributable to preparation prior to excavation.

In the vast majority of surface coal mining operations the compressive strength of the material to be mined falls well within the realms of capability of this machine. However, there were pertinent questions that needed answers.

Where would it no longer be economic to mine using the CSM, and become more economically viable to use the rippers and other earth-moving equipment available? How would areas of higher compressive strength material affect the machine’s performance, in terms of wear and tear on a cost per hour basis? What are the necessary structural and mechanical
adaptations necessary to enhance the performance of the machine under a specific set of conditions?

A number of large mining or excavating equipment manufacturers offer either handbooks or some other data set which outlines predicted machine performance and behavior for a specific set of conditions; this thesis attempts to outline those sets of conditions and to predict machine performance parameters for a specified range.

From this, there is a need to index or model and measure these parameters qualitatively and quantitatively.

1.1.2 Goal and Objective. This research was designed to address the issue of mechanical excavation in terms of its productivity limitations in a surface coal mining environment.

Productivity can herein be defined as a ratio of the following:

\[
\frac{\text{Tons Coal Produced}}{\text{Man-Hours Worked}} = \frac{TonsCoal}{Man\text{-hour}} \quad [1-1]
\]
A sample calculation from research into surface mine productivity (Nilsson, 1988).

\[
\frac{526.4\text{M tons coal}}{113.9\text{M man-hours}} = 4.6 \quad [1-2]
\]

In coal strip mining it is demonstrated from equation [1-2] that productivity has steadily increased from 1975 (3.2 short tons per man-hour) to 1986 (4.6 short tons per man-hour) (Nilsson, 1988).

However, the other main aspect of this research was to illustrate quantitatively those limits within which mechanical excavation is significantly lower in cost (expressed as $ cost per unit produced), than comparative or current mining methods.

The primary purpose of the thesis is to provide a function for the extensive quantity of geophysical data available as logs at many mining operations and determine if there exists any way of converting that data to the corresponding geotechnical physical properties and subsequently provide an index that gives a good correlation
between the machine performance parameters and the primary physical properties derived from this data.

The problem of identifying and outlining the operating and productivity cost model for the CSM in the excavation of predominately lower tensile strength material from the mining site requires an approach that identifies those areas where an increased or above average cost will be incurred.

The short term objective is to prove whether or not the connection between the geophysical data and a reasonable assessment of the machine excavation costs and performance is at all feasible. This will require the development of a path that relates one set of parameters to another and subsequently derives one set from another.

A set of parameters needs to be established that outlines the productivity model so that under any given set of conditions producers potentially interested in using this system may simply and easily determine if this is a viable alternative to the in current system. (See note under "Data Limitations").
Most large mining companies today, in the early exploration phase, define their total in-place reserves through a stratigraphic and lithologic framework. This usually delineates reserves by geophysical logging, and may include core testing.

This study was launched to determine if there were a relationship that could be defined in moderately simple terms, between the data available from geophysical logs and the performance parameters from the Continuous Surface Miner (otherwise referred to as the MSE 3500), that was employed in tests. Whether or not such a relationship can be proved or disproved is important, but at the same time the author seeks to establish that there exists a set of parameters that can be used to specifically identify machine performance on a 'local' scale, for example, this index should be capable of determining the machine's optimum cutting performance in a sandstone channel, a common feature in surface coal mines.

The problem of identifying and outlining a productivity and operating cost model for the CSM in the excavation of
predominantly lower tensile strength material requires a procedure or method that identifies those areas where an increased or 'above average' excavating cost will be incurred.

In selecting a suitable piece of equipment with the capabilities to fill the roles required of it, criteria which must be met include an assessment of machine performance and costs (excavation costs as a proportion of the overall operational, mechanical and overhead costs) in the area that company proposes to have the machine running. In particular, areas of both optimum and poor productivity must be defined, including specifying the optimum bit/tooth configuration for the application, each case being unique.

An evaluation of the Surface Miner in several different scenarios is required in order to establish the most favorable operating and performance conditions, and an assessment of the most appropriate transportation system; this must haul continuously and thus not reduce the efficiency of the system. This study in its entirety may not be feasible within the limits of this report; subsequent
suggestions are therefore outlined in the recommendations section.

Finally, there needs to be a complete evaluation of the Surface Miner in comparison to the current mining method in order to establish the cost savings where appropriate. This section has been abbreviated in order to fulfill the appropriate research requirements for this report.

An index of this type would be unique to the mining industry because, due to the novelty of the Surface Miner, there has not been any effort yet to qualitatively and quantitatively define the machine's performance under different conditions. This has already been established in other areas of mechanical excavation, specifically in the study of roadheaders and tunnel boring machines through research introduced by McFeat-Smith and Fowell in 1977.

As these studies, and studies of alternative, more traditional types of surface coal mining equipment, have proven themselves invaluable as a tool for providing quick, inexpensive methods of evaluating several pieces of
equipment, it can be shown that there exists a need for this type of analysis.

The model proposed is one in which one set of parameters can be derived from another; this is not a new concept as M'Feat-Smith, in an investigation initiated for the NCB describes a method of determining the performance parameters of a Dosco roadheader from the corresponding rock properties.

In the present model however, two main criteria must be met; in the first, it is intended to utilize the extensive ‘library’ of geophysical data as a precursor from which the rock properties and subsequently the specific performance parameters can be determined, and secondly, the accuracy and validity of the developed model must be established through a comparison with actual machine performance data.

1.2 PROPOSED MODEL

1.2.1 Introduction. The overall concept of the model to be introduced is a simple robust regression analysis in terms of those variables most likely to influence the optimum path.
The model derived is a method of developing a way of predicting aspects of machine performance parameters and factors influencing these from their corresponding rock properties.

This model attempts to utilize large quantities of data available in the form of geophysical data to which many mining companies have access.

This data is converted in two stages; firstly in standard format from the geophysical data to the geotechnical and geological parameters. This step is generally easy to establish since there exists a good correlation in general between each set of data. The data is converted initially by means of a gross transformations using a Lotus 123 graph. The whole data set correlated into four specific and identifiable sets which were then identified and described according to their respective geologic and physical (or geotechnical) properties. In this case they could be identified as coal, in which two distinct types could be recognized, silt, shale and sandstone.
The model endeavors to prove or disprove whether or not a relationship can be derived from the physical properties of material at the mine site and the performance of the machine at various localities in the mine or test site. This is not an unusual approach to machine performance analysis, and has been successfully attempted in prior research; where this model is considered unique is that it predicts projected performance data by incorporating the large quantities of available geophysical data into the algorithm and deriving the material properties from this data where possible.

1.2.2 Definition of the Model. The initial conversion of data from large data sets to identifying distinctly different sets of data, in this case lithologies, and subsequently deriving, recognizing and describing relationships that exist between these is atypical of a regression model.

In this case a robust regression is carried out on the complete data set in order to determine those variables
which influence the data set the most, or have specific ‘weights’.

From these the factors influencing the analysis may be determined and an equation is developed in each case describing the relationship between two or more sets of variables.

Finally the relationship between the Uniaxial Compressive Strength and the Specific Energy. From this a range of values can be established which show the Specific Energy required to excavate a particular suite or range of rock types.

Other variables may contribute to the operating efficiency of the excavator and in a more sophisticated model it would be preferable to include these in the final solution; an example of those factors affecting performance at this stage is abrasivity and the subsequent costs associated.

1.2.3 Path Algorithm. The path algorithm is a descriptive method of relating one set of parameters to another describing their relationship in each case.
The path algorithm in this case is derived as a result of a sequence of correlations between respective data sets.

These data sets are first plotted as graph plots in order to determine those variables between which a good correlation is determined to exist. The most appropriate correlations are selected for the required or chosen variables to be used.

The data is reduced so that the selected variables which, in this case, may indicate performance and abrasion factors are derived from this sequence of variables and can be described using an expression.

A path describing this method and illustrating the relationship between actual variables is shown in Figure 1.

It is advantageous to optimize the path by reducing the number of steps required before reaching the selected variables. This reduces the amount of error incorporated into the algorithm which increases with each step.

One important aspect of the path algorithm is how well it lends itself as a system to computer programming, hence
Figure 1. Flow Chart demonstrating the Variables Involved in this study and their relationship to one another.
efficiently and rapidly interpreting and deriving large quantities of data from large data bases.

1.2.4 **Data Limitations.** The acquisition of data by any method invariably incorporates a certain degree of error, be it by the sampling method or human error introduced during the testing stage or interpretation of those results.

The incorporation of these errors has tried to be taken into account where possible in two ways; firstly, the results of the machine's performance in different strata as a function of productivity, are interpreted using a range of values.

Secondly, it is acknowledged, throughout the analysis, where it is felt that those errors could significantly affect results and subsequently, those findings have been incorporated into the results accordingly.

An additional limitation may occur when data is 'screened' in order to remove those data points which exhibit unusually extreme values (high or low); since the initial data set constitutes only 59 points, by removing only one or two 'rogue' values we may be essentially
converting the data set to an artificially altered data set that is no longer representative of true or ideal conditions.

The purpose of screening the data was to remove those "wild" variables. These were obvious in the transformation as persistently occurring outside the regular data group. They are also evident in the data sets and in the initial data. The principle reasons for screening the data in the first place were:

Lack of sample integrity
Bad sample correlation

Lack of or poor sample integrity often occurs when samples measured contain faults or anomalies that may affect the results during testing, i.e. causing premature mechanical failure; this can be due to cracked samples, samples that are too short or too long, places of failure, or slippage or areas in a sample within which another lithology may occur, eg. sandstone or mudstone lenses in a siltstone.
These samples are noted in the record provided with the test results. They are listed in Appendix 3.

In addition, because the data set is only 59 points, it may not be a large enough to be accurately representative of the background that it came from.

In the regression analysis, a degree of validity is established by the use of the t-statistic or Student’s t which seeks to establish those areas where results can be declared valid.

Because of the limitations encountered in deriving a meaningful relationship between several variables in this case it is not recommended that the data be applied directly to a similar mining technique at a different locality; however, it may be possible to transfer the concept of this model and system of analysis to alternative excavation scenarios, where the necessary assumptions and adaptations can be made prior to implementation.

1.2.5 Assumptions. This research is intended to accomplish two objectives; firstly, seek to establish whether or not a relationship exists between two sets of
variables, and secondly, if the relationship does exist, quantify and describe it by means of a set of equations for each step. It became necessary to delete some of the variables to be used in order to keep the analysis simple. The data set represented in Appendix B is the one that is used in the final analysis.

The first of these is to establish that the data set group used is representative of the general lithology and conditions at the test site.

The second assumption is that the test group can be divided, broadly, into 4 separate and defined categories; these are termed, sand, silt, shale and coal. Whilst these sets may not strictly meet geological classifications of these terms, they are only intended to be descriptive.

The third assumption, which we can almost immediately assume is misleading, is that there is little or no variation between individuals in each defined data set. This corresponds to the note made earlier concerning the limitations of the overall data set size.
The fourth assumption is that those "wild" or "rogue" variables are assumed to have no effect on the remaining data points in the analysis.
CHAPTER 2

LITERATURE REVIEW

Extensive work has already taken place in the correlation of machine performance parameters with their relative rock properties. Of these the most significant to date include work by McFeat-Smith and Fowell, Roxborough and Phillips and others. Research to date has almost exclusively concerned roadheaders and tunnel boring machines (TBM’s); whilst these are independent systems they are not mutually exclusive. What they have in common with the CSM is that they are all mechanical excavation methods, utilizing mechanical methods to excavate lower and moderate strength material rock efficiently and in a cost-effective manner.

One of the most fundamental omissions of this research is that no precedent for machine performance parameters of a continuous surface miner has yet been established. Thus there is a need to establish a set of criteria for machine performance parameters, excavation characteristics and such requirements as the correct bit configuration and shape.
McFeat-Smith developed method that headed work to determine the machine performance parameters in a Dosco roadheaders as part of a research project sponsored by the National Coal Board.

A correlation of rock properties with machine performance parameters in roadheaders provided important data linking geological characteristics of the work site with mechanical performance and made a significant impact in the field of mechanical excavation techniques by predicting and defining field limitations of the roadheaders in a mining environment. This theoretical research was successfully borne out during field testing in a drivage in a British colliery.

This method employed direct testing of rock samples from a variety of headings where roadheaders were working. From this a rock-property matrix could be set up. This entailed determining which properties affected or influenced the cutting performance the most significantly.
It should be noted here that the slightest variations in rock type by lithology influence cutting eg., mudstone is affected by:

- discontinuity spacing, and
- rock hardness;

however, the author notes that this could be more influential than first realized, for such lithologies as sandstone and shale. This will only be known when results of the machine performance and bit wear versus lithology are fully realized.

Although a "considerable controversy" still exists over which parameters influence rock cuttability and abrasivity the most, McFeat-Smith and Fowell defined those that they believed to be most influential by choosing a wide range of properties and then selecting those that appeared to be the most indicative.

Two predominant factors emerge in this discussion that influence cuttability and abrasivity; these are defined in this discussion as being the specific energy index and an
index of cutting wear. Rock Cuttability, as defined by the Specific Energy, and be predicted from the following:

- Indentation hardness
- A Deformation Coefficient

A degree of Cutting Wear may be predicted by use of the following parameters:

- Rebound Hardness
- Quartz Content
- Cementation Coefficient

From these two parameters, by means of a set of Predictor Equations, using a Multiple Curvilinear Regression Program, the following parameters can be established:

- in-situ performance
- penetration rates
- tool consumption

Earlier research (McFeat-Smith et al., 1977), principally in the fields of mechanical cutting characteristics of material types and optimising pick cutting for the rock characteristics in each application, has received considerable attention in the literature. In addition considerable
advances have been made in studying the variations in cutting characteristics and efficiency of different cutter types.

Research into mechanical rock excavation began about 30 years ago with the first attempts to understand rock breakage. Roxborough noted that coal mining appeared to be particularly amenable to breakage by mechanical excavation (Fowell et al., 1976) and in the early 1970’s the advent of mechanized excavation in the coal industry was marked by the introduction of continuous miners into the "notoriously hard" coal of the South African coal seams. This was considered the 'acid test' of the technology under field conditions.

Initially the research was primarily systematic experimental and theoretical analysis into the pick cutting action and the relationship between the cutter and the rock behavior, however this field test indicated that the basic relationships established in the labs bore true under field conditions.
Research by Roxborough (McFeat-Smith, 1977) indicated that the in the cutting of rocks with picks the main principles were applicable within the range of 4 to 80 MN/m² and research indicates that although work was principally concerned with work across the spectrum of coals from the weakest to the strongest, these basic principles, when applied to the design of efficient cutting systems, also included a wide variety of other strata types. Amongst those lithologies occurring within this range are sandstones, siltstones, shales and limestones that have a broad range of physical properties including a wide range of compressive strength values. These are particularly significant findings in terms of this authors research, since more information is conveyed concerning a broader range of material types that the initial examination of a coal suite would imply.

This work also had a significant effect in establishing those optimal cutting tools type, shape and configuration for the environment. Of particular interest is a comparison of rotary cutters and drag picks for chalk cutting in which
a comparison was made between four separate pick types in order to establish the most favorable arrangement for cutting in the chalk material. This again is principally experimental and theoretical analysis and investigation of the cutting characteristics of the Lower Chalk, eg. the power limitations which are a function of the specific energy made available. This subsequently resulted in optimizing the design of the cutting head.

In addition this research a number of other researchers have also provided important information in the field of mechanical excavation, establishing those principles to find the most efficient coal cutting action (Pomeroy 1968, Roxborough 1973).

In his cutting theory Pomeroy observed that the volume excavated by a pick was greater than the volume theoretically "swept" by the path of the pick as it travels. This was referred to as the "breakout" and subsequently the "breakout angle".

Pomeroy also observed (Pomeroy and Brown 1968), that the breakout angle remains constant at depth, within reason-
able limits, for different depths when cutting stronger rocks.

Evans' theory (1962) established the cutting force required for a wedge penetrating coal has been shown to be paralleled in at least three other different rock types; shown in the following equation:

\[
F_c = \frac{2t W d \sin \frac{1}{2} (\frac{\pi}{2} - \alpha)}{1 - \sin \frac{1}{2} (\frac{\pi}{2} - \alpha)}
\]

(2-1)

where:

- \(F_c\) = force on the wedge in the direction of cutting at the instant of failure.
- \(t\) = tensile strength of steel (bit)
- \(d\) = depth of cut
- \(W\) = width of wedge
- \(\alpha\) = wedge rake angle

By assuming that the arc of failure is circular and tangential at the wedge tip to the bisector of \(\pi/2 - \alpha\), thus the tensile cutting force may be derived.

Evans' theory works for at least three sedimentary rocks as well as it works for coal; thus assuming that there are no basic flaws in this theory both the measured and the
theoretical values for the wedge force can be considered equally applicable. Discrepancies occur however, between direct pull and indirect Brazilian tensile values, but the trend for each remains the same.

Roxborough finds in his research that a 'marriage' between the force cutting theory of Evan's and the geometry of the groove produced during cutting as a function of the width of the pick, operating depth of cut and subsequently breakout angle, provides a conjectural derivation for specific energy. This is shown in Equation 2-2.

\[
\text{specific energy } SE = \frac{F_{c'}}{A \cdot L}
\]

(2-2)

where:
- \( F_{c'} \) = Force required
- \( A \) = Breakout angle
- \( L \) = Operating depth of cut

Roxborough and Evans' results can be transposed directly to mining costs; these costs are associated with the bit or tooth wear rates relative to the material being cut. This in turn may be affected by design parameters.
CHAPTER 3

FIELD STUDY

In the following section an outline is given of the study area, including history and geology at the test site, and the current mining methods in use.

3.1 STUDY AREA

The study area in which tests were carried out is an operating surface coal mine located approximately 10 miles from the town of Gillette in N.E. Wyoming. The study area comprises about 6440 acres (or about 2607 hectares).

The mine exhibits many of the characteristics of a large, Western coal strip mine in the Powder River basin. It produces high tonnages (around 900,000 tons/month) of low Btu/lb., predominantly sub-bituminous rank coal in a fairly simple cyclic truck-and-shovel operation.

3.1.1 History. Wyoming has the largest calculated strippable reserves in the United States, the estimated total being 22,165 million tons of sub-bituminous coal and lignite (97.7% of which is sub-bituminous). In the Powder River drainage basin there is an estimated 70 per cent of the states total strippable reserves; in 1978, 10 mines in
this area alone produced 60 per cent of the state’s total coal production (Table 1).

Table 1. Wyoming Coal Production 1978, 1979. (Mt)

<table>
<thead>
<tr>
<th>Wyoming Basins</th>
<th>Strip Deep Total</th>
<th>Strip Deep Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder River</td>
<td>35.5 0 35.5</td>
<td>48.4 0 48.4</td>
</tr>
<tr>
<td>Platte River</td>
<td>12.1 0.4 12.5</td>
<td>10.3 0.3 10.6</td>
</tr>
<tr>
<td>Green River</td>
<td>9.9 0.3 10.2</td>
<td>12.0 0.4 12.4</td>
</tr>
<tr>
<td>Total</td>
<td>57.5 0.7 58.2</td>
<td>70.7 0.7 71.4</td>
</tr>
</tbody>
</table>

(Elevatorski, 1980).

Wyoming is traditionally a high strip mining coal producer; in 1978 and 1979 it led the Western States in the production of coal with tonnages of 58.2 and 71.4 million tons respectively. Strip mines in Wyoming have consistently outproduced underground coal mines, generally producing a lower quality sub-bituminous coal.

Whilst mining initially began in the Green River area of Wyoming, enormous reserves were indicated in the Gillette-Wright area, and in 1925 the first strip mine in Campbell County opened up with the Wyodak Mine.

In the late 1960’s interest in the Gillette-Wright area was stimulated and production expanded. The huge increase in activity in the Powder River Basin was principally due to an
increase in the demand by local; Mid Eastern and Southern power plants for low sulphur coal. Many new mines opened up, among these the Belle Ayr Mine in 1972, which in 1978 became the single largest producer of coal in the United States, in excess of 15 million tons per annum.

The Gillette-Wright area (Campbell County) is by far the largest producer in the state followed by Kemmerer (Lincoln County) and thirdly by the Hanna-Seminoe Reservoir area (Figure 2).

Today mines in the Powder River Basin are facing a number of different problems which have caused them to reassess their mining strategy. Besides facing stiff competition from imported coal and domestic coal from Eastern and Central mines that have become more competitive, particularly in the light of enhanced longwall technology, there is also competition from alternative power sources, such as oil, gas, nuclear energy and clean energy. More and more often power plants are being built or adapted to systems that do not utilize coal as an energy source. This has enhanced competition amongst coal producers, particularly those of Western, low sulphur coal producers.

Mines in the study area principally rely upon long-term contracts but may also cover 'spot sales' where required.
Figure 2. Map showing location of study area and coal deposits in the Powder River Basin.
The Caballo Mine for instance, supplies a large proportion of its coal to the Houston Lighting and Power Parish Plant at a delivery cost of $23.60 per ton. These high transport costs, huge tonnages and purchase type contracts are typical of many of the mining operations in the Powder River Basin and represent a large proportion of the overall mining costs. Efforts were made to improve this situation by the installation of a slurry pipeline but this failed, and subsequently these costs appear to remain fixed. Since this time alternative solutions have been examined and proposed to cut mining costs; amongst these are the concept of improved efficiency in the mining method.

This thus identifies coal production, mine maintenance and management as the only potential areas in which cost reductions may be made; of these, coal production is the most amenable to a reduction in the cost/ton.

3.1.2 Geology. The Powder River Basin is located in the North Eastern part of the state of Wyoming. This is a broad synclinal basin with very shallowly dipping seams, from 1 to 3 degrees. Very little complex folding occurs; there is little or no dip at the mine site, on the order of 1 to 2 degrees, except where local tight monoclinal or anticlinal dips (folds) occur. The Powder River Basin may be
divided into two formations; the **Wasatch** (Eocene) and the **Fort Union** (Paleocene). Both of these occur in the test area.

The sedimentary sequence comprises predominantly depositional periods of the Tertiary, Paleocene and Eocene Epochs, and latterly forms the early part of the Cretaceous Era.

The Tertiary coals tend to be sub-bituminous or lignitic whereas the Cretaceous coal are generally bituminous or sub-bituminous. This implies that the depositional environment may have changed somewhat dramatically towards the end of the period, around the beginning of the Cretaceous, becoming increasingly deeper, and possibly being subject to an intense folding event at a later time. This is at least partly a speculation here. Two major coal seams in the Fort Union formation are mined at the test site, including a number of smaller rider seams. There are two main seams; the upper seam is referred to as the Roland seam, and averages 27.4 feet in thickness (8.3 meters) whilst the lower seam, referred to as the Smith seam, averages 70.5 feet (21.36 meters). The lower seam may also be sub-divided further into three parts referred to here as the A, B and C seams. The coal at the mine site is be classified as Subbituminous Rank A.
Coal seams are commonly 10 to 29 feet in thickness, however they are frequently much thicker in the test area, often exceeding 70 feet in thickness.

In the test area itself the coal quality typically averages 8535 British Thermal Units per pound, and contains approximately 5.82 per cent ash, 0.43 per cent sulphur and generally low moisture content.

Overburden and parting material consist of sandstone, shales and siltstone. These range in terms of testing by physical properties, from an average of 720 psi for shale to 2400 for silt and 12,000 psi or higher for sandstone with some sandstone samples up to 25,000 psi. About 10 feet of the outcrop and subcrop portions of the seam have been exposed to heavy oxidation and form clinker at the surface.

The principal coal seam is the Wyodak seam identified as "strippable deposits" in the Figure 2 (U.S Coal Mine Production: Keystone Coal Industry Manual). Strippable reserves are defined as those having a maximum overburden thickness of 200 feet.

3.2 CURRENT MINING METHODS

Mining is currently carried out with a truck and shovel system which is cyclic by nature and typical of numerous coal mining operations in the Powder River Basin.
Drilling prior to loading and hauling is by electric rotary drill rig drilling a 3 inch diameter hole. The coal itself may be blasted prior to loading. The holes are loaded using an ANFO prell mixture (Ammonium Nitrate and fuel oil) and then initiated using an electric round.

Coal is then loaded using 55 and 70 cubic yard dipper P and H electric shovels. Power to this equipment is supplied by means of a trailing cable in the mine.

Coal is loaded at the test site mine into 120 ton rear dump Lectra Haul Unit Rig trucks. Loading can take anywhere from 5 minutes to 14 minutes depending upon influencing factors including operator ability, mining conditions, queue time for trucks, etc. These trucks may also have side boards to increase the load carrying capacity due to the density of the coal (Around 80 lbs/ ft$^3$) in order to optimize the amount of coal hauled per trip.

Overburden is loaded in much the same way, using trucks and shovels; topsoil is stripped and stockpiled in predetermined areas of the mine. Topsoil removal (about 4 inches) is contracted out and excavated using graders and scrapers. Topsoil piles are graded and seeded to preserve integrity until reclamation proceeds.
CHAPTER 4

MECHANICAL EXCAVATION

4.1 THEORY OF MECHANICAL EXCAVATION

Mechanical excavation is, in this context, the excavation of material using mechanical methods to break or fracture the rock; these may be defined as picks or cutters or bits and can cut the rock either in compression or tension.

In mechanically excavating mining equipment the cutting elements are arranged in a certain array or configuration on the cutting head, (Roxborough, 1985). The cutting head may be located either beneath or mounted on the front of the machine.

Mechanical excavation has been shown to be especially applicable in the field of coal mining and in the excavation of other lower strength tabular deposits such as gypsum, talc and evaporates.

Recently a machine was tested at the proposed site that was a scaled down version of the machine that the company hopes to implement at the site eventually. This was a 3500 bcy/hour machine as opposed to the 4500 (minimum) bcy/hour machine proposed machine. (Calculations connected with the equipment are concerned with the 4500 machine unless otherwise stated). In addition the test machine was rubber tire-
mounted whereas the final machine will be track-mounted, on tracks either similar to a Caterpillar D-9 or those manufactured by Krupp.

Mechanical excavation has become increasingly important, particularly from the late 1960's with the implementation of early forms of the continuous miner into South African coal mines, (see 'Literature Review').

Much testing has been done by the National Coal Board in the UK on establishing the cutting parameters affecting Dosco roadheaders by examination of the cutting mechanism.

Roadheaders are much cheaper than full-face Tunnel Boring Machines and are considered more versatile, however roadheaders cannot cut such high compressive strength material as efficiently.

Cutting conditions in an underground coal mine driveways change so rapidly that comparisons of pick performance are "tentative" at best (Hurt and McAndrew, 1984). It should be mentioned here that conditions here are optimal for most mechanical excavation systems when the area to be mined is of a fairly homogeneous nature, flat or gently undulating with little or no tectonic activity, few joints and low abrasivity.
4.2 Design Considerations and Parameters

Primary design considerations in the design and application of any continuous surface excavator are the design parameters surrounding the cutting mechanism.

It has been shown that the cutting mechanism, usually in the form of picks or bits mounted on a drum or actuating arm, are more prone to the effects of stress from wear and vibrational effects than any other part of a continuous excavating machine.

In surface excavating machines it is also critical to maximize the machine size in order to take advantage of lack of size constraints whilst maximizing the available productivity.

Specific applications in the mechanical cutting of coal may vary considerably, in particular including the pick shape, spacing and configuration.

Barker (1964) showed that in the cutting of coal versus other material types, viz. parting material and overburden consisting of sandstones, shales and siltstone, that the basic relationships between the cutting parameters were still in effect and could still be applicable in most cases; however, certain differences became evident, principally that when these relationships were applied to non-carbonaceous material the pick forces required to cut a unit volume
of material were increased proportionally and the energy ratios were often different.

4.2.1 Cutting Drum. Earliest attempts to apply pavement breaking technology to the mining of coal and overburden resulted in the drum remains inconveniently situated beneath the structure of the machine. In later efforts the cutting drum was mounted on the front of the machine where it could be easily accessed and the design proportions increased.

The first attempts at the innovative design of a large pick shearer drum were in 1966 with the design of the MRE. Roxborough design of shearer drum; details on the cutting forces on the drum are described in Barker et al., 1964. The deep cutting concept was first introduced in order to reduce the respirable dust concentrations in the mine atmosphere (Black et al. 1978). It was found as a result of this research that the cutting efficiency was significantly improved as a result of increased depth of cut up to certain limits.

Some research completed on the physical interaction of a rotating wheel of an LAD with the ground (Partrucco et al, 1978) has conclusively shown that this application can be directly related to the rotation of the cutting wheel of the
continuous miner and the forces interacting with it. The vehicle wheel-ground reactions are illustrated in Figure 3.

A critical parameter in the design of the cutting drum is the rotation direction; this dictates to a large degree the resultant cutting action, either in tension or in compression. If the machine is cutting in ground that is stratified, it is optimal to implement a reverse rotation so that the machine is cutting in compression.

A situation may be developed however, for example in the cutting of a lens of sandstone one finds that excessive amounts of energy are exerted upwards due to lifting the entire lens plus a large area of material overlying the lens (Figure 4).

This is also a good case for arguing in favor of 'staggering' the pick configuration of the drum so that there is a grater force exerted by an individual pick upon an area, and the resulting fracture that develops may be exploited by each of the following picks in sequence, illustrated in Figure 5.

4.2.2 Cutter Tool Selection. Under optimal cutting conditions the drag bit provides the most efficient cutting action in mechanical excavation; as Roxborough (1973) pointed out, these cutting tools are considered mainly "a
Figure 3. Forces acting upon the Cutting Drum (Partrucco et al, 1978).
Figure 4. Schematic to illustrate the effect lenses of sandstone may have on the cutting action of the Continuous Surface Miner.
Figure 5. Pick Configuration Illustrating the 'Staggered' arrangement of buckets and picks on the cutting drum in order to maximize efficiency.
tool for use in soft rock". 'Soft rock' being defined as that below 80 M Pascals, whereas the poor cutting conditions were defined as those where the rock is equal to or in excess of 80 M Pascals, highly abrasive or may be considered 'massively jointed'. Under these conditions the pick may begin to experience problems in cutting rock efficiently.

Coal cutting concepts (Evans and Pomeroy, 1966), which are described in some detail by Roxborough, can be broadly transcribed to other strata; those principles governing the design of picks include angle of attack, shape of pick, size and type, speed of pick in the groove, depth of kerf and the cutting of corners.

The mechanism by which the picks break off chips of rocks proposed, in this case, to be a dragging or scooping motion ie. cutting occurs in tension. Abrasive characteristics of the material being mined are extremely important in the selection of the appropriate bit type; these may have a good deal of influence on mining costs, particularly in cases where material with a broad range of abrasivities is proposed to be mined using continuous surface miners. For the test machine, the current bit types may be either a wedge bit, typical of those used on the leading edge of a shovel dipper, or conical bits.
The following definitions are made in order to specify several key elements fundamental to the theory of cutting tools and pick interaction with the material; each will be discussed briefly in turn. These are important to the analysis in that they are directly representative of the specific energies involved during excavation.

1. **Specific Energy (S.E.)** is the key element to this research; although perhaps not the most accurate indicator of machine productivity, S.E. gives a prognosis of work done or energy expended to excavate one unit of (mass or volume) rock. This may be calculated using several methods. In this research S.E. is calculated from known field results of production rates during trials, and the energy expended during an excavation period of time. It may also be calculated as is shown in the ‘Literature Review’ from Roxborough. In this study the Specific Energy is defined as:

\[
\text{SPECIFIC ENERGY} = \frac{\text{Horsepower-hours}}{\text{bank cubic yard}}
\]
Specific energy is reduced as the depth of the cut is increased for all bit types. However, higher rates of production may be achieved and subsequently production efficiencies may be increased as lower power is required for cutting a unit volume of rock. In the case of surface continuous miners, this may mean researching the most appropriate type of bit type, bit configuration and spacing and drum depth in the kerf so as to utilize these opportunities.

2. The **Mean Cutting Force** \( (F_c) \) is a critical cutting parameter; when multiplied by the distance cut it gives the work done by the pick.

3. The **Mean Peak Cutting Force** \( (F_c') \) indicates the transient stresses that the pick will be required to endure during actual excavation.

4. The **Mean Normal Force** \( (F_n) \) is a measure of the force required by the pick to achieve and maintain the depth of the cut in the hole. This determines the machine weight and the required crowd force.

5. **Mean Peak Normal Force** \( (F_n') \) determines the mechanical durability of the cutter relative to the rock being cut.
Both the drag ($F_c$) and normal ($F_n$) forces increase as the depth of the cut increases; this relationship varies however with bit type and several equations have been developed to estimate the cutting force for different drag bits. In each of these cases tensile failure is assumed; this is appropriate in this study due to the nature of physical properties of the material at the test site.

a) chisel pick drag force (Evans 1961)

$$F_c = \frac{2 \ t \ d \ w \ \sin \frac{1}{2} \left( \frac{\pi}{2} - \alpha \right)}{1 - \sin \frac{1}{2} \left( \frac{\pi}{2} - \alpha \right)}$$

b) conical bit drag force (Evans 1984)

$$F_c = \frac{16 \ \pi \ t^2 \ \alpha^2}{\cos^2 \delta \ u}$$

where:  
- $d$ = depth of cut  
- $w$ = bit width  
- $t$ = rock tensile strength  
- $\alpha$ = front rake angle  
- $2\delta$ = point angle  
- $u$ = rock compressive strength
In order to take advantage of maximum efficiency in the cutting action and keep drag and normal forces as low as possible Evans and Pomeroy (1966) recommend maintaining the rake angle at about 20° and the clearance angle between 5° and 10°.

The main agent of destruction of picks in the rock cutting environment is thermal stress which causes breakdown of the tungsten carbide in the bits.

4.3 CONTINUOUS SURFACE MINING TECHNOLOGY

In the field of continuous surface mining equipment, several machines are available, and a brief examination of each of these is made in the following discussion.

Increasingly, mining equipment manufactures are beginning to make inroads into a potentially very lucrative aspect of the coal mining market. Traditionally these manufacturers are those who had been producing larger, less selective and less flexible mining systems, such as the Bucket Wheel Excavator.

As requirements change they now tend towards the application of continuous mining system that is more flexible than conventional mechanical excavation systems, and frequently this has meant the adaption of in-place technology to the problem. A point in case is the adaption and imple-
mentation of the Caterpillar road and pavement breaker, the PR 750B, to a gypsum mining operation in Gypsum, Colorado, (Murakami 1990).

There now follows a short discussion on each of several continuous surface miners currently available:

The Huron Easi-Miner, Model 1224, is an example of the types of equipment available to coal operators today.

This machine is closest as far as being compatible to the Satterwhite machine in terms of yards excavated and the method of excavation, however there are several fundamental differences that should be examined. It is capable of excavating, without prior preparation, approximately 2800 short tons per hour of coal and up to 4000 cubic yards of overburden per hour. No data is available on the compressive strength of the material being cut for either of these figures.

The Easi-Miner seen below in Figure 6 is a track-mounted unit with the cutting drum or mandrill, located underneath the machine between the tracks and slightly towards the front of the machine. The machine operates with on track riding the highwall. This design can conceivably cause problems as for the cutter drum cutting a clean kerf against the highwall.
Figure 6. Bucyrus-Erie Huron "Easi-Miner"
The cutter drum is 13.5 feet wide and can cut to a maximum of 24 inches plus or minus 1 inch! Accuracy that was initially only offered by the continuous miner. Selective mining to this degree of accuracy is typical of these surface continuous miners.

This similarity can be extended to the cutting head design in which picks are arranged so that the cutting action is similar to a roto-mill or auguring device. This causes much regrinding as the material is moved towards the center of the cutting head before it is transferred to the belt and conveyed to the rear of the machine (Figure 7).

Regrinding of material has the effect of enhancing the amount of dust produced as a result and this causes a difficult operating environment. In addition poor bit wear rates and penetration rates, increased vibration and a substantial fines production can all be contributed to this cutting action.

The cutting head design is also the source of another interesting anomaly in that the rotation of the head is a forward or conventional rotation (Figure 8); this means however, that the picks are in each case, shock loaded each time they impact the material to be cut. In other words the picks are cutting in compression as opposed to cutting in tension, or 'pulling apart' the material to be cut. As
A 7-foot-diameter cutting head, with 44 carbide-tipped teeth, cuts the coal, feeding it onto a conveyor.

Figure 7. Auguring action typical of the 'Easi-Miner'
Forward Rotation of the 'Easi-Miner' results in shock loading to picks resulting in point fractures developing and increased wear rates.
impact loading, or shock loading occurs, both the carbide at the tip and the block that the pick is mounted on (welded to), may become fractured.

This procedure results, obviously, in considerably higher pick replacement rates than would normally be necessary, whilst at the same time restricting the machine from mining higher compressive strength material due to design parameters.

Problems may also develop in the cutting and handling of plastic type material due to over-torque of the picks on the cutter head.

The machine design initially incorporated a design that meant that the direction of rotation of the cutting head was in fact opposite to the direction of travel, however difficulties were encountered in that the small picks utilized, being that they were attached directly onto the cutter head, without benefit of loading pockets or suchlike, were unable to throw the material over the cutter head and onto the conveyor belt behind.

It should also be pointed out however, that the direction of rotation on the cutting drum may also mean that the machine moves forward more efficiently than its counterparts, due to the fact that the direction of rotation is the same as the direction of travel.
Additionally, the machine is also substantially lighter (120 standard tons) than the Satterwhite-McNally machine (420 standard tons), and subsequent operating costs are therefore also lower. It is fair to note here, however, that the MSE 3500, while substantially heavier, is also a higher productivity machine.

Efforts have been introduced to increase the size of the machine but as yet these are unsuccessful, as without a substantial corresponding weight increase to act as a counterbalance, the machine becomes very unstable.

The Easi-Miner is powered by a 1200 Hp diesel engine and has been shown to have substantially reduced the cost of producing a ton of coal. It has successfully loaded 170 ton dump trucks in as little as 3 minutes. However, it should be noted at this stage that this machine is principally restricted to lower tensile strength material.

Currently a Huron Easi-Miner is successfully cutting coal and low strength (around 2800 psi) interburden, or parting material at the Jacobs Ranch Mine 50 miles South East of Gillette, Wyoming, operated by the Kerr McGee Coal Corporation.

Wirtgen began with the adaption of its concrete-breaking and asphalt milling technology in the early seventies and through an extension of this road-milling theory came up
with a design for a surface miner that theoretically could selectively mine not only coal but also gypsum, limestone, talc, bauxite, tar sands and a variety of other applications.

Once again, as in the Easi-Miner application, the cutter head was mounted underneath the machine between the four tracks, in this case mounted forward and aft. In addition the cutting tools were again arranged in a helix fashion so to auger material towards the center of the drum, thence to an integrated conveyor belt and discharge conveyor.

The Wirtgen machine, shown in Figure 9, experienced lower performance rates; the Wirtgen machine at the top of the range, the model 4200 SM/1600, with a cutting width of 13 feet 9 inches and a maximum cutting depth of 24 inches (on the order of the Easi-Miner), produces approximately 1962 cubic yards an hour under conditions that are compatible to those in the study area. Due to the design of the cutting head the production rates are considerably lower than those of the Satterwhite Excavator or the Easi-Miner.

The Krupp Surface Continuous Miner shown in Figure 10, otherwise known as the McNally-Satterwhite Continuous Surface Miner, is considered as the preferred excavator in this case, and is shown to exhibit design characteristics that
Figure 9. Wirtgen Miner.
Figure 10. General Arrangement showing details of the Krupp Surface Excavator 3500 used in this analysis.
are more advantageous in both ease of excavation and speed of excavation as well as versatility. Krupp recently acquired the McNally Group and has finished a series of successful tests at the test site.

Although overall power requirements of the Krupp machine are considerably higher than those of the Easi-Miner, around 2750 Hp including losses, and overall machine weight is substantially higher also (total operation weight is 820,000 lbs or approximately 420 tons), it is misleading to assume that this means that the Krupp Excavator is less efficient. Larger power requirements arise from increased machine weight, however, this improves the overall cutting performance of the excavator by providing a vertical component of force that is directly transferred to the cutting drums and hence the picks.

In addition, the machine produces a significantly higher tonnage per hour, and overall cost/ton of material excavated are subsequently lower than those of the Easi-Miner. The operating costs are calculated in Chapter 9, "Cost Calculations".

The machine also exhibits the capability to mine sticky or plastic material just as efficiently as it mines harder material. This can be directly attributed to the bucket arrangement on the cutter drum (Figure 11).
Figure 11. Bucket Arrangement on the Krupp 3500 prototype; (buckets are arranged in such a way that they assist in the 'scooping' action consistent with an upward cutting motion from the rotation of the drum. This also assists in expelling material as it is dumped onto the conveyor).
The cutting action of the Surface Miner revolves around the configuration of the picks on the cutting drum, which are arranged in rows of four along the leading edge of the bucket; (Figure 12). This results in a successful cutting action as the material in the case of plastic or elastic conditions, can be scraped or scooped out of the ground, by the dragging action of the bucket lip. In the case of harder or higher compressive strength material the picks are angled so that they cut upwards into the bank, causing a radial fracture to develop along the plane of the arc tangential to the direction of cut (Figure 13). This is possible due to the direction of rotation on the cutting drum being reverse or opposing the direction of the mining advance.

As a result of this and several other features, such as an increased weight to horsepower ratio, a heavier frame, and different design, the Krupp Excavator has the capability of cutting a variety of harder materials, such as hard coal (anthracite) in the range of 4500 psi and up, hard limestone, siltstone or shalestone containing bands or lenses of silicified sandstone.

From recent tests the optimum range for cutting efficiency appears to be from about 1800 to 4500 psi.
Figure 12. Picks are either conical or wedge-shaped and mounted, four in a row, on a block, which is in turn welded to the lip of the bucket.
Figure 13. The cutting action typical of reverse rotation as in this case initiates a radial fracture that is developed in a plane of arc tangential to the cutting direction, as shown in this diagram.
So far tests indicate that the most serious problem appears to be the large quantities of dust produced, however efforts are being made to deal with this using a variety of dust suppression methods such as water sprays mounted inside the leading edge of a shroud that has been proposed to be mounted so that it covers the cutting drum during operation. A shroud covering the cutter drum then poses the question of whether or not such a device would restrict the performance of the machine as it sumps down into the cut initially.

The buckets arranged on the cutter drum also allow the cutter to successfully carry excavated material over the top of the advancing drum and deposit it in the conveying system behind the drum.

The cutting tools, tungsten carbide tipped teeth which are actually conical bits, are arranged so that they in fact cut with a dragging action; in tension. These tools are also easily accessible for the purposes of replacement and repair, resulting from an improved design.

Higher production rates are possible from a variety of factors, in particular, the machine can cut a deep kerf, up to half the overall diameter of the cutting wheel, in this case 11.5 feet, and the cutting technique results in an over-steepened face such that the material effectively 'falls forward' into the advancing cutter drum (Figure 11);
in addition, the highwall against which the machine is moving remains smooth and flat.

This machine is extremely mobile in confined areas, having a turning radius of close to 65 feet which results in a more flexible and adaptable mining approach. It is also capable of mining selectively and continuously in broadly horizontal or undulating seams, and under good conditions is capable of mining selectively to plus or minus four inches accurate.

Additional models to take advantage of the continuous miner theory have been variously attempted and tested in Austria and West Germany; these are the Alpine Voerst and the Paurat C Miner respectively. Both the Paurat Miner and the Voerst machine are technologies that evolved essentially from previously existing pavement cutting technology. Whilst they have had success in cutting and removing topsoil and additional material under other circumstances, they have yet to achieve the same levels of success in economically and efficiently removing coal and overburden in a producing situation. The Paurat Miner exhibits the auguring action of the cutter drum at the front.

The Satterwhite/Krupp Excavator was selected to be the machine tested for suitability as a potential mining system to replace the current truck-and-shovel and drill-and-blast
method in place at the study area, based upon its demonstrated capabilities to remove coal and overburden in an efficient and cost-effective manner.
CHAPTER 5

METHOD OF ANALYSIS

5.1 THESIS DATA ACQUISITION

The initial data set (Appendix A) was derived from an amalgamation of several sets of data retrieved from field analysis and laboratory test results.

5.1.1 Status of the available data. Geologic modeling of the deposit took place during early exploration and development phases. Of the overburden geology, over 2000 holes have been drilled and an extensive geophysical logging program has been carried out for each of these. Where the data is available only on magnetic tape it must be made available in a form where it can be easily read. From this an interpretation of the geology in the overburden may be assessed.

In the following evaluation of the relationship between geomechanical, geophysical and geological properties of the coal and overburden, data was made available from a sum total of only 6 holes (59 samples), and as such may impose certain limitations on upon the degree of detail that can be reasonably expected in the results.
5.1.2 **Geophysical**. Six holes were drilled in the lease; these comprise NRH-1033, 1036, 1039, 1035, 1037 and 1040. These holes were chosen for this analysis because they represent approximate sections parallel with and perpendicular to the current pit.

Century Geophysical, the logging company contracted to drill the holes, logged the holes to determine the following properties:

- apparent density
- caliper (deviation in hole diameter)
- natural gamma
- resistivity

Core was logged on-site and the results were stored on magnetic tape and had to be integrated into the data sets manually. It was decided latterly, to digitize the remaining data in order to incorporate it into the data sets. In reducing the geophysical logs it became necessary, from practicality constraints, to average the data over 2 foot increments. This may, however, cause problems, since most sandstone lenses requiring identification frequently occur at less than 2 foot thicknesses.
5.1.3 **Geological.** The geology was mapped, both on-site by a company geologist, as it was removed from the hole, and again in more detail at the CSM EMI where photomicrographs of the core revealed the mineralogy and textural aspects in correspondingly more detail. In this analysis the author has chosen to delineate several different types of material and these can be defined upon the basis of their respective physical properties; these are:

- sandstone
- siltstone
- shale
- coal

These terms are purely descriptive and do not necessarily correspond directly to the actual lithologic or geologic properties of any of these rock types. However they are assumed to correspond fairly closely. In each case a range of values is satisfied for each set of conditions, for example, the term "sandstone" denotes those lithologies which comprise sandy material with a large\(^1\) percentage of silica present eg., siltstone with a large percentage of sand, silicified siltstone which may contain large boulders.

\[\text{Large in this context includes anything } \geq 25\% \text{ Si}_2\text{O}_2\]
5.1.4 Geomechanical. The core samples from the holes drilled (listed above) were sent to the Colorado School of Mines Earth Mechanics Institute rock testing lab for a full geomechanical investigation. This included the density measurements, acoustic wave (sonic log) properties, static and elastic dynamic constants, unconfined uniaxial compressive strength and Brazilian tensile strength, Poisson's Ratio, Moh's hardness and Cerchar's Abrasivity test.

5.2 PROCEDURE TO BUILD MODEL

This section deals with the selection of those variables to be included in the final analysis.

5.2.1 Introduction. In order to perform a complete regression analysis on all data sets it is necessary to determine those variables that can be shown to influence the model. The procedure required to complete this was by means of a considerable statistical analysis. Several statistical reduction methods were applied to the data set to ascertain the closest and most accurate representation of the inter-relationships between these sets; of these, the method of analysis chosen to reduce the data is multiple regression analysis. The software package chosen for this method is the Number Cruncher Statistical System.
5.2.2 Multiple Linear Regression. Multiple Linear Regression was chosen as the method to be used because of it's relative simplicity, ease of application and the author's familiarity with the method. Using this technique it is comparatively easy to build a model that can be used to describe a set of conditions.

This procedure is dealt with in considerably more detail in the following chapter.

5.2.3 Selection of Variables. Of all of the properties listed above in the geophysical logging and the geomechanical investigation, certain tests, such as the Cerchar’s Abrasivity, were screened out of the analysis fairly early on in the investigation. This was due to the readings, whilst obviously being a critical aspect in any analysis entailing an study of abrasivity, providing a very poor or narrow range and one that simply did not provide significant changes in terms of deviation between lithologic types. For this reason, Cerchar’s test was considered redundant in this analysis.

Resistivity, a significant method used widely in the correlation of sandstone channels in coal mining areas, was also removed from this analysis, because, although broadly indicative of different lithologies, there were significant-
ly wide and inconsistent variations in the data returned, attributable to the presence or absence of water in the drilling process. Even when circulation fluid was temporarily halted during the drilling procedure, data inconsistencies still existed that could not be tolerated in this analysis.

In order to provide a simple model that could be easily adapted to changing environmental conditions, the selection of the appropriate variables required those variables to represent as broad a set of conditions as possible. The criteria for the selection of variables also required those variables to have the best correlation coefficients as possible.

Finally, data sets were chosen on the basis of those that displayed the most obvious and significant correlations.

Earlier research indicates that one of the most valuable criteria to establish would be the Uniaxial Compressive Strength, which can be related directly to the Specific Energy, and is a good indicator of in-situ cutting performance.

Contributing to the cutter wear aspect is Abrasivity; abrasion is seen as a significant problem in the application of continuous excavators, particularly in the light of
increased bit wear and vibration-induced wear and tear on the machine frame. This results in substantially increased bit costs as a percentage of the overall mining costs.

In this study the effects of abrasion on performance standards are not measured, however, in an increasingly complex model this factor would contribute significantly to the results.

Abrasivity has been established through extensive work with the National Coal Board in the UK to be a leading contributor to mining costs in continuous excavation systems; in the UK alone costs were estimated to be 500 million pounds.

Atkinson attributed severe and excessive wear in mechanical excavation to the "complex digging actions of continuous excavators".

Certainly digging action is a principal contributor in abrasion, however probably as important is the material to be dug. In this case the principal problems are grain shape and size, as well as the type of bonding in the matrix, material hardness and compressive strength of the rock. However, it is also true that even weak rocks can cause high cost and excessive wear. This due to jointing or fracturing or the existence of weak clay bands in an otherwise abrasive material with a high percentage of silica present.
Free silica, or the percentage of quartz in a unit volume of rock, is considered to be a good index of abrasion. The abrasivity of a sample is usually determined using Cherchar's Test of Abrasivity.

Current available indices of abrasivity and cutting potential were established in 1977 (McFeat-Smith and Fowell, 1977), which define those physical and mineralogical characteristics of material as indicators. Mineralogical characteristics are defined as being the percent silica (as mentioned before), and the percent of magnetite and hematite, hard minerals that are indicative by percent contribution of Moh's Hardness to the total hardness.

Other physical characteristics are the grain contacts, size and shape and the cementation type, if this exists, expressed as the Cementation Coefficient.

5.2.4 Generation of Data Sets. Data sets were initially set up on the mainframe; geomechanical data was input corresponding to the position of the sample from whence it came on the in the entire log, from the results of the CSM EMI investigation. The final geophysical data was incorporated into the data sets by digitizing the data as described previously; it should be noted here that certain inconsistencies may exist in the accuracy of the record in setting
up a model from these results, since all the geophysical
data was not obtained the same way. It is preferable to
remain consistent with the methods used by the logging
company and that point is noted here.

From the mainframe the data sets were transferred to
Lotus 1-2-3 files on the PC. This made the generation of
graphical plots fairly simple. Some problems were encoun-
tered during the transformation and in retrospect it may
have been easier to set up the initial data sets on the PC
to begin with.

5.2.5 Transformation Generation. Gross plots were
linked initially on an arbitrary basis. However, since the
density values provide a connection between the core testing
and the geophysically logged values, then it can subsequen-
tly be considered logical that this should provide the basis
against which to offset particular variables in the trans-
formation.

A log transformation, taking the log to the base 10,
which has the effect of stretching small values of \( x \) and
condensing large values of \( y \), should also be considered.
This may be valuable in reducing certain sets of data where
vary wide ranges exist. Caution should also be exercised
however, since this may simply turn into another way of saying the same thing twice.

Two predominant factors emerge from the transformations:

- as expected with density increase, rocks are correspondingly more brittle,
- have higher acoustic velocities, etc.

Lithologies separate out, as one would expect, into identifiable groups, and then further segregation occurs within these groups, causing a distinct bimodal pattern. (This bimodal segregation may also be caused by insufficient data available in the data base for this type of analysis.)

(It should be noted that these transformations were made on the basis of geomechanical data only).

5.2.6 Correlation of Log Samples. Samples for the purpose of geomechanical testing were correlated to the logs by a hole number and a sample identification number (consisting of core number, log id., and PVC pipe number.) These correlations are close but not always accurate, and may be as much as several feet off in the log sequence.

Mostly, however, the log samples correlate well with their given position on the log and can be used with a reasonable level of confidence.
CHAPTER 6

STATISTICAL ANALYTICAL TECHNIQUES

There are two parts to this analysis; firstly, to determine the extent to which a relationship exists between the geophysical logs and physical properties, and then to quantify this relationship. The second part of the analysis comprises quantifying the relationship between the best relationship described and the index used to describe machine performance, specific energy. Past research indicates that this is likely to be the relationship between the compressive strength of the material and the specific energy measured in hp-hr per bank cubic yards, so it is necessary to remain cautious in making a decision that could be biased in this regard.

Compressive strength and specific energy are inherently related due to specific energy being the horsepower required to excavate a bank cubic yard of material; this is a function of the strength of the material to be excavated, thus a strong correlation can be assumed to exist even before one has been ascertained.

Ultimately it was desired to make a direct link between the geophysical property of material at the mine site and the specific energy of the material and cut out the interme-
diate physical property link altogether. This so that the method could be applied to a situation at an operating site in order to make a quick evaluation of machine productivity at the site prior to mining.

The following evaluation was designed to test the relationships between all of the primary units involved and determine which of these contributed to the algorithm most significantly. In each case a number of different statistical analyses took place and the most appropriate was selected. A more detailed analysis followed using the chosen statistical technique and conclusions were drawn, from these results, indicating which regressed variable was to be selected.

Statistical methods are a commonly used technique for determining the validity of the relationship derived between one or more sets of variables in a model. From this an equation may be developed which describes fully the sundry variables associated with the equation and their contribution in terms of magnitude and scale to the equation.

Care has to be taken in analyzing the data and developing the equation that all the variables contributing to the equation are contributing to the same extent and that for each variable the slope is the same, i.e., their net contri-
bution is either positive or negative and adjusted accordingly (Fish, 1986).

6.1 MULTIPLE LINEAR REGRESSION ANALYSIS

The multiple linear regression analysis provides a method of examining the affiliations between all the variable sets entered and determining those variables that are most likely to statistically contribute to the equation.

Multiple linear regression is used to formulate a best fit equation for each variable; it is then necessary to apply the closest fit and consequently the best fit equation may be established for each of the separate relationships.

This method of statistical analysis was chosen over the other methods available for several reasons:

1. Linear Regression is a simple way of relating one set of variables to another and determining their degree of correlation. It was desired in this analysis not to use a more sophisticated method of analysis due to the number of variables involved, time constraints and ease of application.

2. Initial transformations to determine which variables were more likely to have a good correlation with some
than others are essentially a crude form of linear regression.

3. The purpose of the study was not a detailed statistical analysis, but to determine the degree of relationships developed and whether or not those relationships might be used to forecast specific energy for a miner in a mining environment.

6.2 DISCUSSION OF STATISTICAL TECHNIQUES

In geostatistical verification of the relationships between geophysical and physical property values, the following statistical techniques were applied:

- Robust Regression
- Univariate Analysis
- Multivariate Analysis
- Linear Regression Analysis
- Stepwise
- Multiple
- Logistic Regression
- Factor Analysis
- Principal Component Analysis
- Cluster Analysis
- Multivariate Scaling
Of these, the first three took place during earlier research and form part of a separate report not available for publication (Weir, 1988). Of the remainder, Logistic Regression, factor analysis and multivariate scaling are not considered to be significant in terms of their contribution to the investigation and shall subsequently be disregarded for the remainder.

Initially a simple robust regression is undertaken to ascertain those variables that are more likely to occur in the final regression model; these are already pre-determined from the analysis of scatter plots or simple transformations.

In this a Goodness-of-Fit test is contrived in order to establish the best fit along a trend or regression surface. This test is made statistically by comparing the overall variance due to the trend to the variance due to deviation, or the standard deviation, of the trend.

In selecting those variables that account for the low or zero weights, i.e. have more influence in the regression analysis developed so far, a Stepwise Regression Procedure (Neter, Wasserman and Keter, 1985) is employed. This utilizes the robust weights as the weight variables, and this stage will complete the production of a tentative model. In the stepwise procedure a search algorithm technique is
employed that incorporates the development of a series of regression models that includes all the significant variables by addition or removal of significant variables until all have been included in the equation.

When including certain factors in the regression equation, it is necessary to screen certain variables selectively in order to remove those factor which appear to contribute but in reality may not be statistically significant.

The coefficient of correlation, otherwise known as the Pearson's r or the Product Moment Correlation Coefficient, is a significant method for determining the degree of association between one or more sets of variables, in this case to assess linearity (Pearson's r is only valid when the relationship between the variables is linear; it is inappropriate to apply this method to variables displaying a non-linear i.e., curvi-linear relationship). This is a nonparametric correlation method and it can be defined from the following equation:

$$r = \frac{1}{N} \sum \left( \frac{x - \bar{x}}{\sigma_x} \right) \left( \frac{y - \bar{y}}{\sigma_y} \right)$$

(6-1)

where:

$\sigma_x, \sigma_y$ are the standard deviations and,
x-bar and y-bar are the means of x and y respectively.

Thus the product term is called the **covariance**:

\[
\frac{1}{N} \sum (x - \bar{x})(y - \bar{y})
\]

(6-2)

The correlation coefficient, r, is an important contributor to the statistical validity of the variables in the equation; this is described using the following equation:

\[
 r = \frac{\text{covariance of } x, y}{\sqrt{\text{var}(x) \cdot \text{var}(y)}}
\]

(6-3)

R², or the **Regression Coefficient**, is derived from R-squared and gives the researcher a reasonable approximation of the degree of correlation between one or more sets of variables where r ranges in value from +1 to -1 and a correlation of zero (0) indicates that there is complete disassociation between the variables; in this case +1 indicates a perfect positive correlation or perfect functional relationship, where as x increases so does y proportionally. (Where there is a perfect negative correlation there is an R² value of -1). Where a correlation is not complete, or in
partial disassociation, the value of $R^2$ exists as a partial fraction. This is the most common association.

It is unusual to achieve a perfect correlation under any other than artificial conditions, therefore we are more interested in determining the "minimum uncertainty" estimate for a particular variable; this is a method using the **Least Squared Method**. This technique is one that combines the squared value of each variable until all the possible combinations have been established eg. for estimating the y-value from the x-value it is the sum of the y-discrepancies that have to be minimized, and this significantly reduces the amount of discrepancy or error associated with a group of points (Moroney, 1981).

It should be noted however, that $R^2$, which may also be referred to as the **Coefficient of Determination**, should not be used as a method for ranking the significant regression models, when the regression is forced through the origin. In this case it is best to employ a more appropriate method for comparing those regression equations and this is the **standard deviation**, which can be described as the sum of the squares of the regression variables (actual data minus predicted), divided by the number of degrees of freedom (Fish, 1987).
A problem in the interpretation of variables is the existence of Multicollinearity, when two or more of the independent variables correlate in a linear regression. Fish (1987) noted that the regression equation, if "used to forecast the dependant variable", may cause erroneous conclusions or results that do not "fit reality". Multicollinearity can be dealt with during the stepwise component of the procedure during which those variables which exist with another variable are deleted.

The T-Statistic, otherwise referred to as the Student t, gives the researcher an estimate of the uncertainty in the normal distribution; this can be resolved by incorporating into the regression equation only those variables that have a specific t value of equal to or less than a specific quantity.

There are three requirements that have to be satisfied when implementing the t-test:

- both samples are selected at random
- populations from which the samples came are selected are normally distributed
- the variances of the two populations are equal

The F test is used to determine if there is any statistical significance that can be associated with the number of data points and degrees of freedom, and should be included
in the analysis for the purpose of ranking those transformations with varying numbers of data points.

Initially, a univariate procedure was carried out to determine the Shapiro-Wilks W for data sets with less than 51 samples (this includes all data sets, except the total data set), and the Normal Kolmogorov-Smirnov D statistic, also a non-parametric correlation, for the total data set.

Attempts were also made initially to model the variables statistically using alternative methods such as Principal Component Analysis (Princov and Princorr); in the case of the correlation analysis, which employed the use of eigen vectors\(^1\) as the predictor medium, this method was sensitive to outliers and screening to remove these resulted in too few observations to justify the continuation of this method. Covariance analysis turned out to be inadequate as a method of correlating the results due to the wide range in variation of results, eg. Young’s Modulus is huge and accounts for almost 100% of the PCA in the first analysis.

(The covariance, characterized as the joint variance or joint probability distribution of two independent normal distributions about their common mean \((x_1, x_2)\), can also be

\(^1\)Eigen values explain the degree of variance in the principal components, ie. we want as few eigen values for the majority of the data set as possible; eigen vales represent the sum of the eigen vectors.
a useful method of determining the degree of variation between two variables visually.

The second 'alternative' method was the Cluster Analysis based upon the average linkage method which gives a firstly, pseudo-f statistic based upon the separation amongst all the clusters at the current level, and second, the pseudo-t$^2$ statistic, measuring the separation between the two clusters most recently joined. Cluster analysis of the total data set (all 59 points, unscreened), indicated two important features of the set; the data appears to be scattered quite a lot, and the clustering indicated poor data separation towards the end of the set. It should be noted that this is where the bulk of the sandstone samples appeared, and may be an indicator of a poorly defined contact, such as a gradational contact, between the sandstone and the siltstone samples, adjacent.

6.3 REGRESSION ANALYSIS

The model building procedure is primarily to determine the legitimacy of the correlations between each of the various sets of data. In the first part of the analysis the data had to be separated into its component parts on the basis of the correlation or "goodness of fit" between the respective variables.
In determining the appropriate variables to be selected for regression analysis, the entire data set was analyzed based upon the interdependent relationships amongst each of these; this was using gross plots using the Lotus 1-2-3 package as discussed earlier.

As mentioned previously initial screening of the entire data set also took place at this stage. This was to remove those data point that lie outside of the general trend or cluster of the main body of data. These outliers are removed for the purposes of generating a correlation but have been included in the graph plots in order to show their respective locations in reference to other data points. The rationale for this is that the outliers, whilst considerably affecting the overall R² and altering the nature of the slope to be generated, if removed, may also significantly affect the accuracy of the end result.

Subsequently efforts are made to keep as many as are reasonably possible in the final analysis, whilst at the same time still being able to make sense of the results.

The second important point to remember in the interpretation of these results is that the analysis is intended to be representative of the data set as a whole, as opposed to individual data sets representing separate lithologies.
This means that it is critical to first observe the relationships developed between variables in the total data set instead of distinct groups; where the independent lithologies become important is in categorizing the groups by their respective geomechanical and geophysical properties and then attempting to establish the appropriate Young’s Modulus and Uniaxial compressive strength values for each case.

In these cases the results of the regression analysis between each set become crucial in determining the validity of each relationship or step in the path algorithm.

The results of this analysis will give us a range of values for each variable assigned to each data set, a probability value, a correlation coefficient, a slope, intercept and a $t$ value.

6.3.1 Interpretation Approach. The data is first separated into four distinct lithologic groups that are defined according to their geological properties. It should be noted here that additional discreet subdivisions of each lithology may occur within these groupings, for example, a sandstone may either exhibit a gradational contact, or contain bands of carboniferous shale, and likewise, a distinct and entirely separate lithology such as a limestone,
may be present in the sequence. It is important to notice here that the methodology used in this study imposes guidelines for the determination of machine productivity within certain types of strata and discrete local aberrations may be introduced which may have to be considered in the final analysis.

In the interpretation of the regression analysis, the results will be discussed for each of these units separately, beginning with the total data set.

In analyzing the results of the data we are not trying to forecast or predict relationships at this stage, however, there are three distinct sets of variables and their inter-relationships that are to be examined:

- geophysical parameters
- physical properties
- specific energy

At this stage in the analysis, the data has already been reduced to a degree in that it has been determined that the best geophysical variable to use is the apparent density, and therefore no other geophysical parameters will be examined.

The data has already also been sorted to determine, tentatively, optimal relationships gathered from the 1-2-3
transformations. It is from these relationships that the logic path is developed seen in Figure 1.

Initially a univariate statistical analysis was carried out on these data sets in the early stages of the research; this confirmed the earlier findings from the 1-2-3 transformations suggesting these relationships to be optimal. Results of the univariate analysis are shown in the appendix.

6.3.2 Interpretation Results. The results of the regression analysis upon the complete data set indicates that there is a gradual but increasing trend that escalates the slope towards the tail end of the data set.

Five physical properties were measured:

- measured density
- Poisson's Ratio
- Young's Modulus
- Compressive Strength
- P wave

In this case we are trying to find the best $R^2$ value between apparent density and physical properties. The complete data set was tested and then regressions were run on each of the lithologies established.

In the first instance using a 'path' we are trying to find a correlation between the apparent density and the
compressive strength in order to prove that an indirect relationship can be established. This can be seen in the path shown in Figure 1. In the second case we are trying to prove a direct link between the apparent density and the compressive strength values by means of a regression analysis. In this case the remaining variables are removed from the equation. Each of the variables used in the path are regressed against the predictor, the apparent density and the regression results examined. It is desired that ultimately it may be possible to predict the specific energy values directly from the apparent density values and so these variables are also regressed against one another.

Initially the sample was broken down by lithology into 4 sample sets which are silt, shale, sandstone and coal, however, this recommendation was rejected in favor of ultimately using the regression values from the entire data set for the analysis. This is because in actual operating conditions the data from geophysical logs will not appear to fall categorically into any one of these sets, rather, it may be interpreted in a wide variety of ways as the on site geologist may prefer.

It should be remembered though that we are trying to forecast not specific values of specific energy at any one time, rather, we are trying to identify for any lithologic
group, whether or not a relationship may be established to exist in that group between the apparent density from geophysical logs and the specific energy values gathered from machine testing.

A discussion of the regression results is presented in Chapter 7, and the model is derived in Chapter 8.

6.3.3 Application of Method. By applying the coefficients produced in each of the regression equations to solve a set of parameters it is possible to forecast within given confidence limits, productivity levels at the mine site for the surface miner in terms of the specific energy for the surface miner in terms of specific energy for a lithology that is known to have a certain compressive strength or apparent density value that can be assigned to it.

The productivity index, specific energy, is in itself not an ideal indicator of productivity levels, since this value may be considered subjective itself as a function of machine conditions, thus there is room in the model for a large degree of error to be incorporated.

Using this routine and knowing the origination point of the data sets from which the regression values are derived, we can apply the results of this analysis to a working situation. For example, we can predict, within certain
degrees of accuracy, that in material that has an apparent
(geophysical) density of 2.01, the corresponding Machine
Specific Energy, in this case applied uniquely to a Krupp
Surface Excavator, will be between 0.142 and 0.561 Bcy/Hp-hr (Table 3).

This methodology may be successfully applied to a
variety of equipment types in different mining applications.

6.4 DERIVATION OF MODEL

In the derivation of the model we are trying to detect
the most suitable relationships between variables: those
that are i) most representative of the lithologic rock type
and ii) that can be clearly and concisely identified as
separate from other lithologies within the suite at the mine
site.

This may become challenging, particularly in an envi­
ronment such as the surface coal mine identified in this
study, where separate and identifiable lithologies may blend
together and form zones of material that is indeterminate in
its nature. These zones must also be identified and thrown
out, as ‘outliers’, so that during the regression analysis
they will not compromise the integrity of the data.

Defining lithologies is to a certain degree, of a
fairly subjective nature itself and unless definitive ranges
are given to describe characteristics of these groupings, the results may be interpreted inconsistently from site to site.

6.4.1 Factors Influencing Model. Due to the random nature of the model a large number of factors may contribute to inconsistencies and error in the forecast values. Some of these factors have already been discussed, such as the method of interpreting geologic differences within a sequence of rock types, interpretation of statistical data and selection of variables for transformation and reduction and machine operating parameters such as operating conditions, operator familiarity, machine condition and mine idiosyncrasies.

Factors which may influence the model are anomalous values, either very high or very low which can give deceptive or distorted results.

Statistical values affecting the model may be such parameters as the t-statistic, probability levels, and the confidence limits.

6.4.2 Optimum Path. The optimum path represents the most efficient way by which a relationship is established between the individual data sets whilst losing the least amount of integrity in the data sets.
Several paths are compared in Chapter 6 in order to establish the path that represents the highest likelihood of acting as a predictor for specific energy. The paths that are examined are:

1. **The flow path.** This path represents those variables transformed against each other in the data set and takes those with the highest correlation coefficient and forms a path with a given sequence from the apparent density to the specific energy. In this path error is accrued at each stage of the path and the degree of confidence with which specific energy may be predicted at the final level is somewhat lower than the respective stages in between.

2. **The direct path.** In this analysis each of the physical property variables regressed in option (1) are regressed against specific energy. Here we are trying to establish which of the physical property values exhibits the highest $R^2$ with respect to the specific energy values from field testing. In this we are hoping that the relationship between Compressive strength and apparent density will have the best correlation, since it is already given that a very good correlation already exists between the specific energy and the compressive strength values.

Finally we shall examine regressing apparent density as the forecast variable directly against specific energy and
examine the result in this case. It would be ultimately, most practical for a mining operation to be able to take data in their library of geophysical logs and directly apply that information, using a model similar to the one proposed here, to be able to forecast levels of machine productivity at the mine site.

This would then allow operators to make an assessment of the feasibility of using this equipment as a mining method, and allow them to make a rough comparison in terms of cost and productivity, to current mining methods in use.

The model is tested before attempting to forecast specific energies from a number of assorted lithologies, which have been defined according to their compressive strength characteristics; the model which forecasts with the most accuracy the correct specific energy for the formation is chosen.
CHAPTER 7

DISCUSSION OF RESULTS

The results indicate that the small size of the data set available was responsible for the variance in results and low correlation coefficients.

The final $R^2$, while only giving an estimate of the general behavior of an interacting set of variables, was a low 0.44, which demonstrates a poor overall correlation, where the plot would show substantial scatter.

Several points are important here; Firstly, it may be possible to improve the statistical performance of the data by several means. Of these the first two include increased screening of variables to remove all outliers, however, this would significantly reduce the overall number of data points and may result in making the analysis less representative and meaningful; in more extreme cases this screening may also have the effect of making the results of the analysis completely meaningless. The second suggestion, which also forms part of the author’s recommendations, is to increase the size of the data set from which the analysis is made to remove the overall error incorporated into the analysis.

Where this model succeeds is in demonstrating clearly that a link can be conclusively established that connects
the geophysical data available, to the specific energy of
the material in-situ, and correspondingly an index may be
established which correlates the estimated cost of excavat­
ing a bank cubic yard of material in material of varying
specific energies. This is clearly illustrated in this
chapter where the succession of steps from which machine
performance is derived is shown.

It is also possible to optimize the machine design
parameters, such as bit geometry and lacing pattern, so that
the excavation costs can be reduced for each material type;
this means achieving the same production rates with a re­
duced horsepower requirement, ie. reducing specific energy
values.

This would entail a more complete analysis of the
cutting forces involved and a preliminary analysis of some
of the design considerations. These is discussed further in
Chapter 11.

In its simplest form, this model establishes the gener­
al arrangement of the relationships developed between geo­
physical parameters, physical properties and a machine
performance index. To validate the results it may be more
appropriate to include actual time-study data and operating
parameters such as operating efficiencies, maintenance
factors, geomechanical indices and mineralogical properties; these are shown in the flow path in Figure 1.

This would accomplish two things; reduce the amount of error associated with the results with a corresponding increase in design complexity.

7.1 RESULTS OF THE FLOW PATH

1. The first stepwise regression was performed using apparent density as the predictor with measured density as the predictor variable. In this case density is predicted with a large degree of accuracy. There are only two outliers in this equation which contribute to the small degree of regression variation. \( R^2 \) is 0.88 and can be predicted with 90\% degree of confidence. Regression coefficient is 0.44 and standard deviation is 0.23 (figure 14).

\[
\begin{align*}
R^2 & \quad 0.88 \\
\text{PROB >R} & \quad 0.06 \\
\text{slope} & \quad 1.07 \\
\text{Intercept} & \quad -0.13
\end{align*}
\]

2. In the second part of the stepwise regression the predictor or independent variable is density; against this the Young’s Modulus is regressed. Young’s Modulus, \( E \), represents the Dynamic Modulus of Plasticity of material and as such we can expect harder or more brittle formations to display a higher Young’s Modulus than softer formations.
Figure 14. Graph to show laboratory-measured density regressed against apparent density.
Figure 15. Young's modulus regressed against laboratory-measured density.
In this case the $R^2$ is only 0.62; this can be expected due to unusually high values of Young's Modulus being calculated from cores tested. This may be accounted for by the predominantly soft nature of the material giving a unusually wide range of values (figure 15).

<table>
<thead>
<tr>
<th>R²</th>
<th>0.61</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROB&gt;R</td>
<td>0.0001</td>
</tr>
<tr>
<td>slope</td>
<td>1.31</td>
</tr>
<tr>
<td>Intercept</td>
<td>-1.73</td>
</tr>
</tbody>
</table>

3. In the third step of the path sonic velocity is regressed against Young's Modulus as the predictor variable. Acoustic velocities are typically better when forecast as a function of the density as there is a direct relationship between increasing rock density and acoustic velocity. Both the P(compression) wave and the S(shear) wave are measured during physical property testing and travel time through the rock is assessed. The P-wave was determined to exhibit a slightly higher correlation against the Young's Modulus than the S-wave, and therefore this was chosen.

In this case the correlation coefficient is 0.82; this may be attributed to the anomalous range of Young's Modulus calculated in step 2 in the physical property testing which cause a lower than expected correlation to be developed at this stage.
Figure 16. Graph showing sonic velocity shear wave regressed against Young's modulus.
4. Using the P-wave to predict Uniaxial Compressive Strength provides a moderately good $R^2$ value of 0.88; this can be directly related to the proportional increase in acoustic velocities relative to increased strength of the sample (figure 17).

The final $R^2$ is a cumulative value of the path and represents the error incorporated into the equation as well as the regressed relationships between all variables involved in this path. This is 0.39 which suggests that the correlation coefficient, whilst acceptable between individual variables in the analysis, is very poor as far as being a final predictor.

7.2 RESULTS OF THE DIRECT PATH

The other option is to attempt to establish a direct relationship between the specific energy as a function of the apparent density.

In this case, the specific energy was regressed directly against the apparent density. The resultant correlation was poor, giving a correlation coefficient of 0.24. Then,
Figure 17. Graph showing compressive strength regressed as a function of sonic velocity.
the specific energy was first regressed against the compres-
vive strength, which was in turn regressed against the
apparent density, yielding correlation coefficients of 0.98
and 0.42, respectively. This path was seen to produce the
best correlations and as a result was adopted as the basis
for the final predictor model.
CHAPTER 8

FINAL MODEL

8.1 INTRODUCTION

The results of this research indicate that the following relationships may be established in the course of three separate stages; these comprise the model. The results of geophysical logging data as a method to predict compressive strength values produce the following equation, also shown in Figure 18:

\[
CS = 4500d + (-7550)
\]

where:

- \( CS \) = compressive strength
- \( d \) = apparent density

The next stage involves predicting the specific energy from the compressive strength values obtained in the first stage. This relationship is also shown in Figure 19; in this case the following equation results:

\[
SE = 0.00012CS + (-0.036)
\]

where:

- \( SE \) = specific energy
- \( CS \) = compressive strength
Predicting Compressive Strength from Apparent Density

\[ y = 4500x + (-7550) \]

predicted values +/- 90% confidence limits

Figure 18. Compressive strength as a function of apparent density
Predicting Specific Energy from Compressive Strength

\[ y = 0.00012x + (-0.036) \]

predicted values \( +/- 90\% \) confidence limits

Figure 19. Specific Energy as a function of compressive strength
In the third stage specific energy is expressed as the energy in units of horsepower-hours, expended to excavate a bank cubic yard of material. From this, knowing the specific energy, one may calculate the production rate of a machine relative to its horsepower consumption; this number includes entire horsepower, including drum motor and auxiliary motors. It is also possible to derive specific energy values directly from apparent density values; in this case the correlation coefficient indicates a poor correlation, however of only 0.29. Reasons as to the poor correlation are given in Chapter 10. This relationship is illustrated in Figure 20.

\[ SE = 0.7895d + (-1.7697) \]

where:

SE = specific energy

\[ d = \text{apparent density (predictor)} \]

**Example:**

From geophysical logs an apparent density of 2.21 is derived. A mining company interested in pursuing a potential new mining lease or extension to their current lease may apply the results of this study in the following manner.

They have two options: firstly, directly derive specific energy values from apparent density which is a more
Predicting Specific Energy from Apparent Density

\[ y = 0.7895x + (-1.7697) \]

predicted values +/− 90% confidence limits

Figure 20. Specific energy as a function of apparent density.
direct method but results in a lower coefficient of correlation, or secondly derive compressive strength values from apparent density values and then the specific energies from compressive strengths.

In this example the latter route is chosen to promote a more realistic approach to the problem.

Geophysical values at the test site indicate a local value of apparent density of 2.21. In order to derive the corresponding compressive strength value, this is inserted into the equation as follows:

$$CS = 4500 \times (2.21) + (-7550)$$

$$CS = 2,445 \text{ psi.}$$

Summarily,

$$SE = 0.00012(2,445) + (-0.036)$$

$$SE = 0.2574$$

Thus, knowing the specific energy, it is possible to calculate the productivity for a machine of a given horsepower, e.g., 1500 Hp.

$$BCY = \frac{1500}{0.2574}$$

$$= 5,827.5 \text{ bcy/hr.}$$

And conversely, knowing the specific energy and required yardage, calculate the horsepower necessary to produce this:
Hp = 3500 bcy/hr (0.2574)

= 900 Hp. (not including losses)

An example is also given at this stage where specific energy may be calculated directly from the apparent density:

\[ y = 0.7895(2.21) + (-1.7697) \]

\[ y = -0.0249 \]

As can be seen in this example, this has resulted in a negative specific energy meaning that this method can only be usefully applied to those apparent densities of 2.25 and greater, and caution should be used in interpreting these results.

A multivariate analysis was not incorporated at this stage since it was felt that a researcher wishing to probe this model should be able to access the path at any one of the stages.

Two principal problems exist with the model developed in this study that affect the final results and conclusions developed; these are the degree of error accumulated through each step in of the algorithm, as represented by the \( R^2 \) value in each case, and secondly, the relatively small size of the data set used in the analysis. The data set is the result of having access to data from seven principal drill holes at the study site which were chosen since they represented sections both perpendicular and parallel to the pit.
being developed concurrent with the study. After screening to remove outliers which, it was decided, would prove to make the results of the study more ambiguous if left in place, the initial data set of 59 points, representing both geophysically logged and material properties, was reduced to 54 viable data points.

Following this, when trying to determine arithmetically from the equation a direct relationship between apparent density and the machine performance index the accrued error and small data set may account for some of the low correlations which exist between the 4 different lithologies defined in the first part of the analysis. (See Table 4 showing correlations).
CHAPTER 9

ECONOMIC CONSIDERATIONS

An economic analysis of mining costs and productivity was carried out for a Continuous Surface Miner of 3,500 bcy/hr. capacity. The estimated costs were compared with the current conventional mining costs to determine the potential cost savings to be gained from the application of continuous mining techniques at the mine.

9.1 MACHINE POWER REQUIREMENTS

The Continuous Surface Miner can be operated as a diesel unit or electrically. Both have advantages and disadvantages; machines that are electrically powered have a trailing cable, in this instance a 7200 V cable which is incorporated into the surface mining environment. This is an inexpensive and easy way to provide power, however it can reduce flexibility and provide potential hazards.

Diesel drive allows enhanced versatility and may be more suitable in applications where small 'spot' sites are to be mined and it is either inconvenient or not possible to provide electrical power.

The prototype model used for the field trials was a 3500 bank cubic yards an hour machine. This machine had an
11.5 ft. diameter cutting drum and has achieved a penetration of 0.64 inches per revolution. In the case of the larger model with a 4,500 bcy/hr production capacity the power requirements are about 2650 hp. This machine is fitted with a 13 ft. diameter cutting drum and crawler mounted to reduce bearing pressure.

The machine horsepower requirements consist of a 1500 hp engine to run the cutting drum and two 400 hp motors are used to generate the power required for operation of all other ancillary equipment, including pumps, energy lighting and displays, conveyor feed motor and locomotion.

The test machine was diesel. The horsepower requirements were calculated from the advance rate in field tests, the plunge of the cutting drum, efficiency factors and the rate of conveyor feed. It was determined that the optimum rate of advance was about 13 feet/min. in order to maintain maximum cutting efficiency. The optimum digging depth was 2/3 to 3/4 drum diameter.

9.2 COST CALCULATIONS

The purchase and maintenance costs for the engines are as follows (personal communication, Wagner Equipment Co.):

a) Purchase Costs:

1500 hp $130,000
400 hp $25,000

b) Maintenance costs:

$0.50 - $0.75 per hp/hour

A 3000 operating hour per annum is assumed from the following basis; firstly 3000 hours was the suggested typical working load on the diesel engines used in this analysis, and secondly, this figure was recommended as an estimated annual average number for the first few years as the machine comes into full commission by Krupp.

Based upon 3000 hours per year operation, a 400 hp engine, for example running at 75% of load for 3000 hours will cost $4,500.00 per annum. This would cover all maintenance, adjustments and overhaul at 10,000 to 15,000 hours.

Assumptions are listed on the following page in order to provide an estimate of costs and productivity in the surface miner:

swell = 1.5
bucket fill factor = 33%
material density = 92 #/ft$^3$(may vary)
cuttability average (may vary)
efficiency factor = 75%
operating time/op. hour = 40 mins.
production rate = 3500 bcy/hour
drum diameter = 11.5 feet
cutting width = 21 feet
wheel rim speed = 150 - 786 fpm
    average = 350 - 550 fpm
wheel tip speed (selected as a result of 72 inch wide conveyor belt) =
bucket area = 35.2 SF
overall bucket width (@ 21 ft. width kerf) = 16.69 ft.

Production rate

3500 bcy/hr * .75 (eff.) = 2625 bcy/hr.
annual operating hours = 3,000
40 mins/hour, thus op. hours/annum = 2,000
annual bcyardage recovered = 5,250,000

Annual use = 2000 actual hours
Operating cost/hour =

Operating Costs

Assumptions:
operating hour/year 3000
weeks/year 50
operating hour/week 60
operating hours/day 10
machine operator $17/hr.
25% fringe benefits $4.25/hr.
ground man (oiler and lube, repair, change picks) $15/hr.
25% fringe benefits $3.75/hr.
crawler/tractor costs (Atkinson, 1978)
pick replacement 1.25/hour
replacement cost = $20/each $25/hour
average conditions
repair factor (average) 110%
**Maintenance costs**

Fuel Consumption: Fuel consumption for the following engines at full load:

- 1500 hp: 75 gal/hour
- 400 hp: 20 gal/hour
- diesel/gallon: $0.75

Thus, assuming 75% load, we can get the following annual fuel costs:

\[
[3000 \times 75 \times .75] + [3000 \times (2 \times 20 \times .75)] = \$258,750.
\]

- Oil and Lube @ $4.25/hour: $42.50/day
- Hydraulic Fluid (add and replace 0.6 gallons/day @ $3.50/gallon): $2.10
- Filters: $24.00/day
- Maint. and Weld (parts and labor): $156.00/day
- Drum repair, cutter replac.: $250.00/day

Subtotal: $1337.10/day

**Labor Costs**

- Operator: $212.50/day
- Ground man: $187.50/day

Subtotal: $400.00/day

Subtotal: $1,737.10/day

Annual use (actual hours): 2000

Operating cost/hour: $173.70

Operating cost/year (adjusted): $521,100

Operating cost/year (actual): $347,400

**Ownership Costs**

Assumptions:
- Depreciation Period: 7 years
- Wyoming State tax: 3%
- Straight Line Depreciation
- Expended Cost
- Insurance: 1% of value * no. of years
- Freight: 15% of initial cost
- Interest on average investment: 16%
- Salvage Value: 20%
- Investment Tax Credit: 10%
- Property Taxes: 5%
### Table 2. Investment Table

<table>
<thead>
<tr>
<th></th>
<th>$US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krupp 4500</td>
<td>6,500,000</td>
</tr>
<tr>
<td>3% Wyoming sales tax</td>
<td>195,000</td>
</tr>
<tr>
<td>estimated freight</td>
<td>975,000</td>
</tr>
<tr>
<td><strong>Total Initial Investment</strong></td>
<td><strong>7,670,000</strong></td>
</tr>
<tr>
<td>Investment Costs/year</td>
<td></td>
</tr>
<tr>
<td>Interest Costs</td>
<td>175,315</td>
</tr>
<tr>
<td>Property Taxes</td>
<td>54,786</td>
</tr>
<tr>
<td>Insurance (* 10 years)</td>
<td>76,700</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>306,801</strong></td>
</tr>
<tr>
<td>lifetime investment costs</td>
<td>2,147,607</td>
</tr>
<tr>
<td>Total for 7 years</td>
<td>9,817,607</td>
</tr>
<tr>
<td>Salvage value</td>
<td>-1,534,000</td>
</tr>
<tr>
<td>Investment tax credit</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Net Ownership Costs</strong></td>
<td><strong>8,283,607</strong></td>
</tr>
<tr>
<td>annualized over 70 years</td>
<td>1,183,373</td>
</tr>
<tr>
<td><strong>Operating costs/year</strong></td>
<td><strong>521,100</strong></td>
</tr>
<tr>
<td>production/year</td>
<td>5,250,000</td>
</tr>
<tr>
<td>Ownership cost/bcy</td>
<td>0.23</td>
</tr>
<tr>
<td>Operating cost/bcy</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>TOTAL COST/bcy</strong></td>
<td><strong>0.33</strong></td>
</tr>
</tbody>
</table>

The present mining costs at the site using a conventional truck and shovel operation average $0.50 to $0.56/bcy. This can be as low as $0.26/bcy, however, as can be seen, the cost savings on the order of $0.17 to $0.23/bcy appear feasible using the Continuous Surface Miner.

Indications suggest that a potential savings over conventional, cyclic drill and blast/ truck and shovel methods of between 12 to 13 per cent may exist; this is illustrated in Figure 21.
Figure 21. Comparison of conventional mining costs to those associated with continuous mechanized mining. (Source: Krupp Industrietechnik)
Table 3 illustrates how the initial investment cost of those mine plans utilizing the surface miner may be substantially lower than that of the conventional cyclic system.

Table 3. Comparison of Krupp 4500 to Conventional Cyclic Mining Systems

<table>
<thead>
<tr>
<th>Investment Costs</th>
<th>Shovel system</th>
<th>KSM with trucks</th>
<th>KSM with conveyors</th>
</tr>
</thead>
<tbody>
<tr>
<td>drill</td>
<td>1</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>shovel</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>KSM</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>truck</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>conveyor</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>conveyor bridge</td>
<td></td>
<td></td>
<td>.5</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>6.8</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Source: Krupp Industrietechnik

Besides mining in a selective and continuous fashion, mining using a continuous mechanical excavation system may also prove to be more economically advantageous when a mine plan conducive to the mining method is employed. For example, by incorporating a mobile conveyor belt into the mine design so that the mobile miner is loading continuously directly onto a following conveyor belt, the continuity of the system is not disrupted, a cost saving of between 29 and 38% may be realized.
This however, requires a substantial change in initial mine plans, such that instead of traditional benches, a long slope with a shallow gradient, optimally of approximately 3 per cent, is maintained. This may expose significantly more coal to the potential problems associated with coal oxidation than would normally be exposed using traditional methods.

In addition, reserves along the lease boundaries or in tight corners may have to be abandoned or mined conventionally.

Other obvious advantages of the Continuous Surface Miner are a reduction in primary crushing requirements, smooth haul roads and the ability to mine thin, undulating seams that might be otherwise inaccessible.

Finally, it is not necessary to discontinue operations in the pit as is required using conventional mining with blasting so that mining may continue in a constant manner.

Some of the problems may be addressed as the surface excavator is successfully and smoothly incorporated into a current truck and shovel operation, loading directly into trucks; this does compromise the continuity of the system however.
In the above comparison costs from drilling and blasting are not included. An initial investment of rotary rig for drilling 8 to 12 inch diameter holes plus bulk loading powder (ANFO) truck would be required, not including the associated periodic costs of operator, drill bits, explosives and detonators. In addition, it would be necessary to acquire the requisite blasting permits and provide a vibration monitoring installation to monitor blast vibration and potential damage.

9.2.1 Mining Method. The surface miner may either be used in conjunction with the mobile conveyor bridge directly behind the miner. In this mine design the conveyor from the miner feeds directly into the mobile conveyor behind the miner at it advances. This conveyor in turn transports material to dump stations some distance from the mining area.

Mining takes place on very wide benches that have a shallow gradient of less than 5%.

In a mine plan that incorporates the current mining equipment into the design, truck haulage already being employed at the mine is utilized. The initial investment is lower in this instance due to the mine infrastructure already being established, however, this system retains some
of the cyclic aspects of the original mine plan and is thus inherently more inefficient.

Studies indicate that in order to maintain the same kind if theoretical yardage possible using a miner/truck system as a miner/conveyor system it may be necessary to increase the number of trucks in the fleet servicing a single miner and possible increase the number of miners. It takes approximately 2.4 minutes to load a 250 ton haul truck with sideboards therefore the amount of standby time is increased.

9.2.2 Cost Savings. The following cost savings may be realized:

1. Cost savings are introduced in the KSM/conveyor mine plan where comparative excavation levels to conventional mining systems may be achieved with a reduced number of operators.

2. Cost savings are introduced by virtue of the mining technique of the KSM leaving a smooth pathway with few irregularities. This results in decreased levels of wear and tear on other vehicle in and around the pit area.

3. Cost savings result from a reduction in the primary crushing requirements.
9.2.3 **Estimated Productivity.** In "Cost Calculations" (9.2) the machine productivity is assumed to be 3500 bcy/hour, however, this will vary as a function of the material to be excavated. In Table 3, a summary is given of the field results of machine specific energy obtained from tests which took place at the mine site; in addition, predicted values of specific energy are also given, as well as results predicted by the author.

It is the resultant field values that are used as data in this analysis in order to prove a relationship between the compressive strength and the specific energy. These are applicable since they were obtained from the test site where the geophysical logs were also obtained.

Productivity may be estimated by looking at the apparent density value of a geophysical log and applying it to the equations developed from the method described in Chapter 8; result forecasting productivity may be assumed to be accurate to within 90% confidence limits.

9.2.4 **Factors Affecting Productivity.** Machine productivity is measured in this study in

\[ \text{Hp-hours/bank cubic yard} \]
This is a function of power required by the machine to excavate a unit quantity of material. Horsepower may vary as the machine parameters change such as

- strength of material
- rate of advance
- depth of drum plunge (optimum is two-thirds wheel diameter)
- condition of cutters
- (weight of machine)

Of these, machine weight is the least significant in contributing to a horsepower increase, and material strength is the most likely. Cutters that are broken, blunt or missing will reduce the cutting efficiency of the system tremendously, particularly if the cutters become caught up in the 'eddy' at the front of the drum as illustrated in Figure and continue to rotate amongst the loose material, becoming 'reground' themselves and causing serious wear to other cutters.

It is possible, knowing the specific energy of the material and the cost per bank cubic yard, to be able to determine cost per horsepower hour for mining; this is specific to the material being mined, however, and does not translate directly to other materials.
In this case average cost for mining 1 bank cubic yard of 4200 psi material is $0.33, therefore divide $/bcy by the specific energy, 0.24, and we come up with a value for cost per horsepower-hour.
CHAPTER 10

CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

1) A model was developed in order to predict that specific energy could be predicted from geophysical data; this was based upon a regression analysis performed. The best correlations were obtained between the specific energy and the compressive strength which in turn was correlated to the apparent density measured from geophysical logging.

2) The predicted machine specific energies were found to correlate well with the field measured specific energies. (Note: It is important to note here also that in order to get a realistic value of specific energy as a function of the material and its properties, it is necessary to know the actual percentage of cutter drum engaged at the face. In the calculations involved in this study this is assumed in each case to be 100%, however, in actual tests the percentage of face engaged ranged from 60 to 80%.)

3) The analysis of field measured and predicted machine performance indicated that the accuracy of the predictions can be improved by taking into account the degree of plasticity which the material exhibits in response
to excavation by a continuous miner. The compressive strength and the apparent density do not clearly reflect the material plastic behavior.

4) In addition, in order to get a more accurate model, it may be necessary to weight material by 'cuttability' as a function of its RQD, extent of jointing and naturally occurring clay.

5) Data were grouped according to the lithologies presented in Chapter 5, and the variables were regressed accordingly against each other. This attempt to interpret the data was unsuccessful, possibly due in part to a large degree of variance arising from a small data set.
CHAPTER 11

RECOMMENDATIONS

As can be inferred from the extent of the material covered in this research, there exists numerous opportuni­ties for the continuation of this type of research in this field; a primary consideration is the innovative technology which shows tremendous potential to evolve and dramatically reduce the excavation costs even further.

1) Design Considerations

The following areas are considered important in achiev­ing and maintaining optimum machine performance:

- bit type
- bit lacing pattern
- bucket arrangement
- RPM
- direction of wheel rotation
- speed of advance

In particular, areas which show excellent potential for improvement in machine performance are the design of the cutting drum, the layout of the picks on the drum itself and the pick types to be used themselves. The latter would involve an extensive analysis of the pick forces involved
(described in Chapter 2), and their performance in different material types, measured during cutting tests. These types of tests and their application are described in detail by Roxborough (1985) and Neil (1990, pers. comm.).

Certain type of bit design may prove to be more advantageous than others under specific cutting conditions, for example, in wet, plastic or sticky material, a blade type of pick with a fairly shallow angle of attack, between 25 and 40 degrees, will effectively ‘scoop’ material up and into the buckets. In dry or rocky conditions a cone-shaped or sharp pick may prove more suitable.

Other considerations to machine design are the already mentioned, rotation direction, which proves to have a strong effect on both bit wear rates and loading efficiency. Designs in the bucket area may facilitate loading and dumping cycles, particularly when sticky or loamy and clayey materials are encountered, so as to improve overall digging efficiencies.

2) Model Approach

Linear cutting tests are recommended at this stage to determine the optimum cutting tool for this type of application in order to reduce the required specific energy. It is also recommended that several types of bits be tested in the material gathered from the test site; this will help estab-
lish the best cutting tool. At the same time it is necessary to establish the optimum spacing for the bits to improve breakout angle, and establish the best angle of attack, or rake angle. It is not known at this stage whether or not the bits employed in cutting during each of the tests were the same type; since this will have an impact upon the specific energy values gathered in field trials, it is necessary to keep all testing conditions uniform.

3) Results of core testing are sensitive to core diameter so that during testing of bits to establish optimum bits it is recommended to use the largest core diameter available so as to keep results consistent, and maintain conditions as close to field conditions as possible.

4) During testing it is also recommended to establish the degree to which the orientation of the bedding planes and joint planes in the core affect results of physical property testing. Since the data set displayed only small variations in general in physical properties, structural anomalies may have a significant bearing on the results. Conversely, "good" factors such as natural cleavage or joints may improve cuttability and lead to erroneous results.

5) It may ultimately be necessary to incorporate into the algorithm such parameters as machine weight, depth of
cutting drum in face (percentage engaged), the type of picks being utilized and their spacing. This then would lead to a more comprehensive and ultimately, more accurate assessment of machine performance.

6) Analysis of bit wear, a significant cost not only for replacement parts but also for reduction in cutting efficiency and replacement time, and performance is critical; two areas that require more immediate investigation are rocks that behave in a brittle or plastic fashion. In particular, "plasticity" is poorly defined; this is examined briefly in greater detail in the following discussion.

7) It is also suggested that an increase in productivity may also be viable from results of previous research that suggests that increased tooth penetration and increased cutting force combined with reduced advance rate and lower wheel rpm may contribute to a substantial production increase, with reduced operating costs as a result of lower engine revolutions (Neil, 1989, pers. comm.); at the same time the lump size (of material produced) is also increased. In some cases this is desirable, but in many cases this simply results in increased costs as a result of crushing requirements and this may offset savings incurred elsewhere.

8) The comparative costs of alternative mechanical excavation systems may also have to be explored more fully,
since this primary economic analysis does not take into account such aberrations and subtleties in costs incurred as local or regional variations, variations due to management practices and contract agreements, e.g., union versus non-union operations, geographical variations onset due to local conditions, such as mining in an extremely cold climate or conversely, extremely hot, and wage variations dependant, largely, upon geographical locations eg., where labor is relatively inexpensive, this may make mechanical excavation redundant.

This is a principal consideration also from the point of view of the large initial investment to be made; apart from the cost of the excavator itself, a substantial support network is also required, either trucks or mobile conveyors, and auxiliary equipment, and in many nations this capital outlay may be grossly prohibitive, resulting in a focus on more traditional mining equipment, particularly if that equipment is also already available as second-hand machinery.

9) As Atkinson (1978) emphasized, in more complex geological terranes, such as those exhibiting multifarious faulting structures or unstratified, non-homogeneous strata, the importance of a full and detailed petrographic analysis in areas where continuous excavation systems are to be
implemented, is critical "because of the complex digging action" can result in unusual wear ratios. It is therefore suggested that the criteria established for the prediction of cutting wear and cost indices in these types of circumstances be analyzed appropriately.

10) In the physical property testing it may be advantageous, and would have been preferable, to undertake a determination of the specific energies of the material tested from the core. This would have meant that at the least, here was one less step in the algorithm, and at best it may have been possible to correlate the geophysical properties of the material directly to the specific energies. A direct link would cut out a substantial portion of that error that is incorporated into the equation as each additional term is introduced. In addition, it may be beneficial to attempt a Schmidt Hammer Rebound Hardness Test, which would also give a good estimate of the plasticity and strength of the material.

An accurate determination of the mineralogy is critical since it is from this that an estimate of the Abrasivity can be made. The importance of petrographic analysis of thin sections cannot be stressed sufficiently; good indications of abrasivity are:
- undulose or "pressure" twinning often indicating 'hard' quartz
- angularity of grain shape, grain contacts
- groundmass characteristics, particularly when the matrix is cryptocrystalline quartz such as chert or chalcedony
- the total percent of silica present by volume, and the presence of any other hard minerals such as goethite or zircon (Atkinson, 1978)

11) Even a comparatively unsubstantial material such as a weak sandstone may show inordinately high levels of wear that become unacceptable as to make the operation uneconomic under extreme conditions, and this can be directly contributed to parameters such as the cementation coefficient or other hardness index.

This method also shows excellent potential to lend itself to computer programming and becoming a widely implemented applications technique. This may also satisfy the conditions recommending increasing the number of samples in the data base from which the analysis is made, and accelerating the data reduction process, particularly during the initial step when the geophysical data is processed. However, it is still necessary to carry out the appropriate geophysical, geological and geomechanical testing initially prior to the application of this method of determination at a site other than the test site.
12) As a final recommendation, it should be remembered that specific energy is not a unique quantity and will depend upon such variables as the pick shape of the cutting tool, in addition to other operational variables. As such, all tests must be standardized as much as possible so that deviations in trial results do not cause inaccurate deviations in forecast results.
REFERENCES CITED


3. Atkinson, T., Selection of Open Pit Mining Equipment


18. Krige, D. G., Geostatistics and the Definition of Uncertainty


APPENDIX A

Complete Data Set Including All 59 Data Points Prior to Screening
<table>
<thead>
<tr>
<th>Material</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Density (g/cm³)</th>
<th>Moisture (%)</th>
<th>Hardness (Mohs)</th>
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</thead>
<tbody>
<tr>
<td>Wood</td>
<td>10</td>
<td>2</td>
<td>0.8</td>
<td>12</td>
<td>3</td>
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<tr>
<td>Metal</td>
<td>15</td>
<td>4</td>
<td>2.7</td>
<td>5</td>
<td>2</td>
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<td>Glass</td>
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<td>1</td>
<td>2.5</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>Plastic</td>
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<td>3</td>
<td>1.4</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
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<td>Description</td>
<td>2.2</td>
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<td>295</td>
<td>5775</td>
</tr>
<tr>
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<td>----------------</td>
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<td>560</td>
<td>970</td>
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<td></td>
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<td>2500</td>
<td>380</td>
<td>610</td>
</tr>
<tr>
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<td>4025</td>
<td>610</td>
<td>7270</td>
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<td>715</td>
<td>6975</td>
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<td>400</td>
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<td>2450</td>
<td>370</td>
<td>6450</td>
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<tr>
<td>marker</td>
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<td>2.27</td>
<td>13200</td>
<td>7.4E+03</td>
<td>10340</td>
</tr>
<tr>
<td>marker</td>
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<td>2.93</td>
<td>43800</td>
<td>6.4E+03</td>
<td>12390</td>
</tr>
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</table>
APPENDIX B

Screened Data Set Used in This Analysis
APPENDIX C

Samples Which May Indicate Poor Sample Integrity
<table>
<thead>
<tr>
<th>Sample</th>
<th>Lithology, Description</th>
<th>Location</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRH 1033 26-6</td>
<td>Shale: light-grey silty streaks</td>
<td>Overburden, main pit</td>
<td>Separated in middle - along bedding plane</td>
</tr>
<tr>
<td>NRH 1033 17 76 2</td>
<td>Pyritic sandstone, cemented</td>
<td>South pit parting</td>
<td>Extremely hard.</td>
</tr>
<tr>
<td>NRH 1033 20 87</td>
<td>Coal: solid</td>
<td>Smith coal</td>
<td>Moist. Separation occurs along bedding plane perpendicular to the core.</td>
</tr>
<tr>
<td>NRH 1033 156</td>
<td>Shale: slightly carb., oxidized</td>
<td>Overburden North pit</td>
<td>Separation along bedding planes.</td>
</tr>
<tr>
<td>NRH 1036 6-28</td>
<td>Shale: grey, solid</td>
<td>Main pit parting</td>
<td>o Extremely plastic</td>
</tr>
<tr>
<td>NRH 1036 6232</td>
<td>Shale: grey, solid</td>
<td>Main pit parting</td>
<td>o Separated 3/4&quot; from top.</td>
</tr>
<tr>
<td>NRH 1039 4 18 3</td>
<td>Shale: slightly carb., firm</td>
<td>Overburden North pit</td>
<td>Extremely plastic when set</td>
</tr>
<tr>
<td>NRH 1039 4 19 4</td>
<td>Shale: firm</td>
<td>Overburden North pit</td>
<td>Separated along bedding planes approx. 40° off horizontal</td>
</tr>
<tr>
<td>NRH 1035 16 77</td>
<td>Sandstone/siltstone (diagonal contact)</td>
<td>Overburden North pit</td>
<td>Horizontal crack 2&quot; from top of sample.</td>
</tr>
<tr>
<td>NRH 1037 12 16</td>
<td>Sandstone</td>
<td>Overburden Main pit</td>
<td>Small size affecting dynamic constants</td>
</tr>
<tr>
<td>NRH 1037 15 3</td>
<td>Sandstone: very hard, very fine grained, cemented</td>
<td>Overburden main pit</td>
<td>Half soft material, half harder material.</td>
</tr>
<tr>
<td>NRH 1040 3 15 3</td>
<td>Silty shale: laminated, hard inclusions</td>
<td>Overburden main pit</td>
<td>Softer material, randomly mixed in.</td>
</tr>
<tr>
<td>NRH 1040 6 81</td>
<td>Sandstone with some silt, very fine grained</td>
<td>Main pit parting</td>
<td>Static elastic constants affected by some internal unconformities.</td>
</tr>
<tr>
<td>NRH 1040 17 87</td>
<td>Sandstone</td>
<td>Main pit parting</td>
<td>Sample partially deteriorated, hard inclusions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Marked lamination with weaker material.</td>
</tr>
</tbody>
</table>
APPENDIX D

Samples Showing Poor Sample Correlation
<table>
<thead>
<tr>
<th>Sample</th>
<th>Lithology, Description</th>
<th>Location</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRH 1037 42 02</td>
<td>Silt, hard cemented</td>
<td>Overburden, main pit</td>
<td>Cementation.</td>
</tr>
<tr>
<td>NRH 1040 27 13 3</td>
<td>Coal</td>
<td>Roland</td>
<td>Very shaley.</td>
</tr>
<tr>
<td>NRH 1037 8 39 5</td>
<td>Coal</td>
<td>Roland</td>
<td>Very solid.</td>
</tr>
<tr>
<td>NRH 1037 9 43 3</td>
<td>Coal</td>
<td>Roland, main pit</td>
<td>Solid, occasional horizontal fracturing.</td>
</tr>
<tr>
<td>NRH 1036 4 17 2</td>
<td>Coal</td>
<td>Roland seam</td>
<td>Higher humidity level.</td>
</tr>
<tr>
<td>NRH 10 35 8 38 5</td>
<td>Coal, solid</td>
<td>Roland</td>
<td></td>
</tr>
</tbody>
</table>