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Bucket Wheel Excavator Study

Final Report

January 1979

Published June 1979

Prepared For

U.S. Department of Energy

Assistant Secretary for Energy Technology

Division of Fossil Fuel Extraction

Under Contract No. HCP/T77-C-01-8914-01

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January 1979

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Prepared For
U.S. Department of Energy
Assistant Secretary for Energy Technology
Division of Fossil Fuel Extraction
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TABLE OF CONTENTS

	<u>Page</u>
LIST OF FIGURES	iv
LIST OF TABLES	vi
INTRODUCTION.	1
SYNOPSIS OF BWE APPLICATIONS IN U.S. COAL MINES	7
FIELD INVESTIGATIONS	17
CASE HISTORY:	
MINE A.	21
MINE B.	24
MINE C.	28
MINE D.	31
MINE E.	34
MINE F.	37
MINE G.	39
MINE H.	43
MINE I	48
MINE J	53
PRODUCTIVITY ANALYSIS	59
BWE MECHANICAL-ELECTRICAL DELAYS	67
BWE OPERATIONAL DELAYS	71

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
MINING SYSTEM EVALUATION AND ANALYSIS	81
MINING METHODS	83
High-Deep Cutting	83
Conventional Mining Approach	86
Dropping Cut Modifications	91
Special Mining Approaches	93
COMPARISON OF EXTRACTION METHODS	95
MINING SYSTEM INFLUENCES	97
Overburden Characterization	97
Problem Areas	104
Evaluation of Cutting Techniques	108
OVERVIEW OF COMMON DIFFICULTIES ENCOUNTERED	111
GEOLOGICAL	113
MAINTENANCE	115
CLIMATOLOGICAL	118
MECHANICAL	120
The Bucket Wheel	121
Mechanical Drive Systems	123
Conveyor and Boom	125
Crawler Assemblies	125
RECOMMENDATIONS FOR FUTURE RESEARCH	127
BWE SELECTION CRITERIA FORMULATION	129
Develop Overburden Test to Determine Potential Problem Areas	131

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
CUTTING RESISTANCE FACTOR EVALUATION	133
RECOMMENDATIONS TO ELIMINATE EQUIPMENT MISMATCHES	140
RECOMMENDATIONS TO IMPROVE BLASTING TECHNOLOGY.	143
RECOMMENDATIONS TO IMPROVE MECHANICAL AVAILABILITY	145
CONCLUSIONS	155
BIBLIOGRAPHY	161

LIST OF FIGURES

<u>No.</u>		<u>Page</u>
1	AREAS FOR POTENTIAL BUCKET WHEEL EXCAVATOR OPERATIONS	12
2	ARTISTS ILLUSTRATION OF BWE/SHOVEL COMBINATION	13
3	ARTISTS CONCEPT OF PROPOSED BWE/ DRAGLINE COMBINATION	15
4	BUCKET WHEEL EXCAVATOR AVAILABILITY/ OVERBURDEN PRODUCTION	66
5	BUCKET WHEEL EXCAVATOR MECHANICAL - ELECTRICAL DELAYS	68
6	BUCKET WHEEL EXCAVATOR MECHANICAL - ELECTRICAL DELAYS	70
7	BUCKET WHEEL EXCAVATOR OPERATIONAL DELAYS	72
8	BUCKET WHEEL EXCAVATOR OPERATIONAL DELAYS	74
9	MECHANICAL, ELECTRICAL & OPERATIONAL DELAYS - BUCKET WHEEL EXCAVATOR NO. 4	76
10	MECHANICAL, ELECTRICAL & OPERATIONAL DELAYS - BUCKET WHEEL EXCAVATOR NO. 4	78
11	BWE MINING METHODS.	84
12	CHARACTERISTIC CYCLOTHEM STRATIGRAPHIC SEQUENCE	99
13	FRICTIONAL FORCE DIAGRAM.	122

LIST OF FIGURES (Cont'd)

<u>No.</u>		<u>Page</u>
14	RESOLUTION OF FORCES	123
15	SPECIFIC CUTTING FORCES OF UNEXCAVATED MATERIAL	135
16	WEDGE TYPE INTERFERENCE FIT TOOTH	147
17	OSCILLATION DAMPING SHROUD (CROSS SECTION)	148
18	MULTI-WHEELED EXCAVATOR DESIGN CONCEPT	150
19	MINIMUM SHEAR WHEEL DESIGN CONCEPT.	152

LIST OF TABLES

<u>No.</u>		<u>Page</u>
1	BWE PRODUCTIVITY DATA	63
2	BWE AVAILABILITY	77
3	CATEGORY DOWNTIME AS A PERCENT OF TOTAL DOWNTIME.	77

INTRODUCTION

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INTRODUCTION

Coal is frequently referred to as "America's most abundant energy source", and all indications, for the near term, suggest that it will retain that status. While the goal of "energy self sufficiency by 1985" seems to be eluding our grasp, coal is playing an ever expanding role in meeting the nation's energy demands. A significant portion of the 437 billion tons of known coal reserves in the United States are suitable for extraction by surface mining. However, to fully develop and utilize these near surface deposits, innovative mining systems and coal utilization technologies must be developed.

From the time mining was first practiced on a large scale, mine operators have sought methods for continuous material excavation. A large scale bucket wheel excavator (BWE), when coupled with a continuous haulage system or in a direct cast mode, offers such a method. While it is commonly acknowledged that a continuous excavating system will consistently out-produce a cyclic unit with the same bucket capacity, the real and imagined constraints to machine availability have limited their widespread use in the United States. At the same time, Eur-Asia has become a virtual showcase of state-of-the-art design, construction, and utilization of large and small scale BWE's. Examples of available technology are the Krupp BWE's working the Hambach and

Garsdorf open pit lignite mines in West Germany. These machines have capacities of 240,000 and 200,000 bank cubic meters per day respectively.

Recognizing the potential role BWE's could play in significantly increasing U.S. surface coal mine production in the near term, the United States Department of Energy, through its Division of Fossil Fuel Extraction, contracted Skelly and Loy to perform this Bucket Wheel Excavator Study. Essentially the study was designed to investigate utilization of BWE's in coal mines. An integral part of the study was an assessment of the current operating status and constraints that influence the applicability of BWE's in certain domestic coal fields. From this basic evaluation of United States BWE technology and utilization, future research efforts aimed at enhancing the potential for BWE applications in United States coal mines were developed...

To accomplish the objectives of this Bucket Wheel Excavator Study, a detailed six month research effort was designed and implemented. Because the primary objective of this program was to recommend future research needs, it was necessary to develop a state-of-the-art understanding of domestic BWE applications. For this reason, initial activities focused on an in-depth review of available domestic and translated foreign literature on current BWE applications. Recent

development and expansion in BWE technology and application necessitated the use of a computerized bibliographic search to provide up-to-date information and expand the working data base.

Concurrent with the literature review, an accurate listing of all active and inactive BWE applications in United States coal mines was developed. During the course of this activity, two mines were uncovered that tried, unsuccessfully, to implement BWE's at their operations. When the inventory of successful (active and inactive) and unsuccessful BWE's at United States coal mines was finalized, each operation was contacted to solicit their assistance. From this, permission was obtained to have field teams visit 7 mines successfully operating BWE's and 2 mines that had not been successful in applying BWE's at their mines. The resulting field studies were designed to examine and evaluate the BWE relative to its specific application, and the general mining system employed.

To enhance the information from the field studies, all BWE manufacturers, foreign and domestic, were contacted for input on their product lines and specific design and operating parameters. As expected, they were all cooperative. At this time it came to light that Barber-Greene was staging an extensive field trial for their rotary wheel excavator. Permission to observe the demonstration was granted,

and the data gathered incorporated into the project.

As each mine visitation was completed, detailed summaries were prepared and data analysis was initiated. The first step was an analysis of the mining methods employed at the sites studied. Both the specific BWE mining approaches and extraction plans and the general mining system employed were evaluated. In conjunction with this, an assessment was made of the system employed at each site and its influences on BWE and overall mine productivity. Evaluations were made of the influence of overburden characteristics on BWE performance from both an application and productivity standpoint. In addition, cutting resistance was evaluated and some design criteria formulated.

Based on the data and general information generated by the field activities and data analyses, areas for future research were delineated and recommendations made. The focus of the research recommendations was on ways to:

- eliminate or reduce operating constraints experienced at current BWE sites
- improve BWE reliability over current levels experienced at United States coal mines
- extend the applicability of BWE's outside of areas of present domestic use

The following report details the activities and results of this research effort.

**SYNOPSIS OF BWE
APPLICATIONS IN
U.S. COAL MINES**

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SYNOPSIS OF BWE APPLICATIONS IN U.S. COAL MINES

Bucket wheel excavators were first applied in the United States at one of United Electric Coal Company's Illinois surface coal mines. The machine, designed and built by Frank Kolbe and other United Electric Coal Company engineers, was put into operational trial in 1944 and had an average production of 960 bank cubic yards per hour. From this start, the "Kolbe Wheels" that followed were quickly upgraded to capacities of 0500 bank cubic yards per hour. This rapid increase in BWE capacity was made possible by the introduction of cell-less wheels, increased wheel speeds, new belting and belt speeds, and chain backed buckets to reduce the problems of sticking material. In 1954 Bucyrus-Erie, working under a United Electric Coal Company license, introduced their BWE to the American market. It was not until 1963 and 1964 that the first large-scale German BWE's were introduced for American surface coal mining applications. From then to fairly recently, the utilization of BWE's in United States surface coal mines has remained relatively static.

Initially, American and foreign BWE's were designed for working in easy-to-dig materials. This severely limited the application of these machines and generally confined their use to areas where at least some of the overburden was glacial in origin or of similar friable

material.

Because of the limited flexibility of the early machines and the limited number of areas where they could be effectively applied, interest in the large-scale utilization of BWE's in United States surface coal mines waned for several years. This is evidenced by the ages of the machines that were observed during the field investigations. With the exception of the unit at Mine H in Washington, the BWE's studied were at least 2, and in some cases 3, generations old and do not accurately reflect state-of-the-art BWE technology. Although the operators of these machines have integrated the latest advances in bucket teeth, conveyor belting and drives, motors, and hydraulics where possible, they cannot match the productivities and flexibility associated with European BWE's.

Application of BWE's in United States' coal mines has been principally concentrated in Illinois around the area where they were first introduced. An exception is the unit in use at Mine H. Additionally, BWE's have been applied, unsuccessfully, in two other areas: the North Dakota lignite fields and the Powder River Basin of Wyoming. More detail on these mines is provided in the Case History section of this report.

A keen interest in the potential for applying modern BWE's

in American coal mines is developing. This renewed interest stems from factors such as potentially high productivity, but the chief impetus is the successful mining and reclamation achieved with large-scale BWE's working the European brown coal deposits. One encouraging note is that BWE's are being closely studied for use in large-scale mining development outside of the conventional areas. Principal among these areas are the lignite fields of Texas and Louisiana. Overburden conditions there are generally such that dragline operations do not require blasting.

Modern BWE's used in a multiseam selective mining system will be given more attention as these extensive lignite deposits are developed because the overall mining conditions are considered ideal for BWE's. Based on favorable topographic and sufficient amounts of unconsolidated overburden, there are additional coal regions where mining conditions could allow the use of BWE's. The map in Figure 1 illustrates areas where the potential for applying BWE's to surface coal mining exists and should be examined more closely. In developing this tentative map, consideration was given to the relatively flat lying coal seams, amenable overburden depths, types of overburden normally encountered, and the capabilities of modern BWE's to mine material that, until recently, was beyond their abilities.

AREAS FOR POTENTIAL BUCKET WHEEL EXCAVATOR OPERATIONS

FIGURE 1

FIGURE 2 - Artist's illustration of BWE/shovel combination.

Figure 2 illustrates a BWE/shovel combination. This system is typical of those employed, at present, in the United States. Figure 3, however, shows a BWE/dragline combination. With the exception of Mine H, such a system has not been used in the United States; however, it is believed that this system could be more effective than the present BWE/shovel methods. Further analysis of this approach is addressed in the Recommendations section of this report.

The interest in applying BWE's to meet the nation's ever-increasing energy demands, coupled with the Federal surface mining regulations (PL 95-87), offers a unique opportunity for manufacturers and mine operators alike to develop new mining strategies that meet this challenge. Strict topsoil handling requirements of the new regulations, if properly addressed by the mining industry, can act as a springboard for the development of new and innovative technology.

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FIELD INVESTIGATIONS

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FIELD INVESTIGATIONS

To develop a basic understanding of the mining methods and common problems faced by companies operating bucket wheel excavators throughout the United States, a program of site visitations was established. The visitations were conducted at coal mines in the United States where bucket wheel excavators operated, facilitating determination of variables and their influence on operational directives.

A preliminary list was devised from information supplied in the RFP. This list contained the tentative location of BWE's in the United States. Following an extensive literature review it was established that eleven mines were presently operating BWE's and that two mines had operated BWE's in the past.

The next step was to contact corporate and mine personnel to obtain permission to visit their mine and observe BWE operations. Four mines were unable to comply with our request for a site visit. In one case, the mine had been closed down and the bucket wheel was no longer in service. Personnel at the remaining three mines felt that this was not an appropriate time for scheduled visits. This established the list of operations to be visited.

A total of nine mines allowed field teams, consisting of a

geologist and a mining engineer, to survey and study their respective operations. Six of the nine mines were located in the Illinois Basin; the remaining three were located in Washington, Wyoming and North Dakota. The field crews initially met with company officers (usually a head of operations, and/or chief engineer) for orientation and to complete a detailed questionnaire which included site specific information concerning unit operations, production and BWE statistics. It should be noted at this point that, in order to be consistent with information received from mine operators, availability figures include mechanical/electrical as well as operational delays.

Field teams subsequently began a two day, one shift per day study and survey of the total mining scheme. This applied only in the case of successful mine sites. Visits to the unsuccessful sites required a one day visit to complete the questionnaire. Personnel most familiar with the BWE were made available and provided valuable assistance and information through the duration of each visit. Wherever possible, general mine scheme and detailed BWE photography were included to enhance the data base. The case histories that follow delineate information received during these visits.

CASE HISTORY MINE A

Located in North Central Illinois, Mine A operates a Demag-Lauchhammer (1965 version) SchRs $\frac{1000}{3}$ - 25. It had originally worked at a company mine in North Dakota from 1965-1968. Due to a high incidence of large rock dispersed throughout the overburden, the BWE was disassembled in the fall of 1968 and sent to this mine. It has been in production at this site since 1969. Operation is on a 3 shift/day, 362 days/year schedule. The BWE is used to remove the 30-40 feet of glacial till and directly cast it across the pit. The machine also serves to replace topsoil in preparation for reclamation.

Although designed to be the primary stripping machine, the BWE works in conjunction with an 80 cu. yd. Marion stripping shovel. The bucket wheel takes the top glacial material and the shovel removes the remaining 60-80 feet of shale and clay. The seam being mined is the #5 (Springfield) coal. It is approximately 4 to 5 feet thick, relatively uniform and dips 3-5% to the northwest.

A 2 inch horizontal drill using 45 foot centers is used to prepare the overburden for removal by the shovel. Approximately 500 pounds of ANFO is used per hole with primacord and blasting caps as the primary detonating agents. A 25 millisecond delay is maintained between shots.

The BWE has eight 1 3/4 cu. yd. buckets mounted on a 30 foot diameter wheel. The stacker boom can be articulated, which allows for specific placement of spoil as required. Movement of material is accomplished with the use of a three belt system. The ladder belt moves the material at 1050 fpm until it is transferred to the intermediate belt running at 1150 fpm. From there, it is transferred to the stacker belt which runs at 1250 fpm. These staggered belt speeds keep the spoil moving to eliminate backup and congestion on the belt.

The only major modification was the addition of 15 feet to the height of the machine. The additional height was necessary to enable the BWE to excavate higher bank material.

Major and potential problems that hamper use of this BWE are as follows:

- 1) The BWE does not run at its rated capacity due to the abrasiveness of the material and scattered rock. When large rock is encountered, it becomes necessary to retract the machine from the digging face until the problem has been resolved. Generally, the rock is dislodged with a dozer and pushed to the shovel for removal.

- 2) Climatic conditions are such that when excessive rainfall occurs, it clogs the digging head and belt system due to the sticky nature of the overburden. Freezing conditions cause frost build-up on the sloped sheet inside the bucket that transfers material to the conveyor. This minimizes the amount of material moved and reduces the cutting production per hour.
- 3) Construction of the roller frame and rollers is such that necessary repairs are made much more difficult due to inaccessibility. There also seems to be a problem associated with the availability of replacement parts.
- 4) Although the optimum pit width is 125 feet, a 150 foot width is required to allow passage of the shovel and BWE since both machines are working on the coal. Passage of the machines occurs because of the mismatch in BWE/shovel capacities.
- 5) According to the operators, the biggest complaint is that the bucket wheel was not designed to work high overburden or work with a shovel. However, until an alternate solution can be devised, this method must suffice.

CASE HISTORY MINE B

Mine B is located within the boundaries of the southern Illinois coal region and operates a United Electric Kolbe W-5 bucket wheel excavator. The bucket wheel assembly is mounted on a Marion 5561 shovel frame and requires a three man crew for efficient operation. It was specifically designed for this mine and intended to work in conjunction with a 70 cu. yd. Bucyrus-Erie 1650 stripping shovel. It has been in production at this site since 1969. Operation is on a 3 shift/day basis with a rated availability of 60% or greater.

The BWE is used to remove the 20 feet of unconsolidated glacial till with the spoil being directly cast across the pit. The remaining 45 feet of gray shale is removed using the stripping shovel. The seam being mined is the #6 (Herrin) coal. It is approximately 5½ feet thick and dips and rolls 0-8% with the general trend toward the southwest.

Blasting is required prior to excavation of the shale by the shovel. ANFO is the primary blasting agent utilizing primacord and blasting caps for detonation. A Bucyrus-Erie 61-R vertical drill is used to produce a staggered 27 foot pattern. Usually eight holes are shot at once without a delay.

As it now operates, the BWE profile dimensions are 426 feet

in length, from bucket to discharge point, and 144 feet in height. At a total weight of 3.3×10^6 lbs., it exerts a ground bearing pressure of 51 psi over a total area of 450 square feet. Crawlers are electrically driven by four 100 horsepower motors and can travel at 35 fpm. A 20 foot diameter bucket wheel, with 8 two cu. yd. buckets, mounted at the end of a 60 foot cutting boom is driven at a speed of 8 rpm by one 600 horsepower motor at 75 rpm - dc. Operators estimate a 90-100% bucket fill factor. This machine is capable of swinging at 0.10 rpm driven by two 125 horsepower motors at 460 rpm - dc, and has a digging range of 27-100 feet above the seam. Each bucket has 6 square shaped ESCO teeth arranged in an evenly spaced pattern. Pre-cutters are not used. Teeth and belting are replaced on an as-needed basis. Buckets are chain and rubber mat backed to facilitate unloading.

The bucket wheel has averaged 32 cu. yd./hour since starting in production. Availability was listed as being 60% or greater. This figure was largely dependent on pit progression and other operational delays. Both digging and stacker conveyors use 60 inch wide rubber belting. The ladder belt is driven by a 250 horsepower motor at 1800 rpm - ac and revolves at a rate of 965 fpm. The stacker belt is driven by a 600 horsepower motor at 1800 rpm - ac and maintains a 1100 fpm rate. This machine has a 60 foot crowd when fully extended. The

ladder crowd is driven by two 75 horsepower motors at 490 rpm - dc and can attain a crowd speed of 29.5 fpm.

The following are major problems encountered by the BWE:

- 1) Since the BWE and shovel run on the coal, a 90 foot pit width is required. This is considerably less than the 150 foot pit width required at Mine A because of the physical size difference in the BWE's. Although actual passage only requires 70 feet, it is felt that the extra 20 feet allows for a reasonable safety margin.
- 2) Although climatic conditions have hampered production elsewhere, this mine has had little problem in this area. However, heaters are affixed to the stacker belt in case conditions warrant their use.
- 3) Due to scattered rock, the machine has been equipped with air and hydraulic shock absorbers. These were specifically designed for stress due to shock loading. These shock absorbers are successful inasmuch as they absorb initial impacts. However, belt coupled, wheel drive mechanisms employing pressure limit switches must be adopted in order to withstand severe shock loads.

- 4) Although seldom required, major downtime results when new pads, crawlers, belts and sprockets have to be installed. These repairs are done on an as-needed basis with no regularly scheduled replacement.

Overall, the mine personnel felt that they have been pretty successful with the wheel.

CASE HISTORY MINE C

Mine C, located in southwestern Illinois, operates a United Electric Kolbe W-5 bucket wheel excavator. It is built on a Marion 5560 shovel frame and has been in operation since 1969. Operation is on a 3 shift/day, 350 days/year schedule. This machine is used to remove the 20-45 feet of glacial material with the spoil being directly cast across the pit. The BWE is also utilized for topsoil replacement. Dozers are used to push the stockpiled topsoil to the bucket wheel for casting onto the spoil area thus eliminating the need for scrapers.

The BWE works in conjunction with a 60 cu. yd. Marion 5761 stripping shovel. The shovel removes the remaining 45-60 feet of shale and limestone. The seam being mined is the #6 (Herrin) coal. It is approximately 5-7 feet thick, uniform with no significant partings and it rolls considerably.

A 61-R vertical drill using a 30 x 33 pattern is used to prepare the overburden for removal by the shovel. Bagged ANFO, with blasting caps as the detonating agent are used strictly for overburden shooting. A 1 millisecond delay between shots is maintained.

As it now operates, the profile dimensions are 426 feet in length, from bucket to discharge point, and 144 feet in height. At a total weight of 3.3×10^6 lbs., it exerts a ground bearing pressure of 51 psi over a

total area of 450 square feet. The crawlers are electrically driven by four 100 horsepower motors and can travel at 35 fpm. A 22 foot diameter bucket wheel, with 8 two cu. yd. buckets, mounted at the end of a 60 foot cutting boom is driven at a speed of 8 rpm by one 600 horsepower motor at 75 rpm - dc. Operators estimate a 75-80% bucket fill factor. This machine is capable of swinging at 0.10 rpm driven by two 125 horsepower motors at 460 rpm - dc, and has a digging range of 27-100 feet above the seam. Each bucket has 8 wedge-shaped ESCO teeth arranged 3 on each side, and 2 on the front. Precutters are not used. Tooth and belting replacement are on an as-needed basis. The buckets are chain and rubber mat backed to facilitate easier unloading of the clay-like glacial material.

The bucket wheel has averaged 1,300 cu. yd./hour since starting in production. Availability was listed as being 50%, this being attributed to operational delays and downtime. Both digging and stacking conveyors use 60 inch wide rubber belting. The ladder belt is driven by a 250 horsepower motor at 1800 rpm - ac and revolves at a rate of 965 fpm. The stacker belt is driven by a 600 horsepower motor at 1800 rpm - ac and maintains an 1100 fpm rate. This machine has a 60 foot crowd when fully extended. The ladder crowd is driven by two 75 horsepower motors at 490 rpm - dc and can attain a crowd speed of 29.5 fpm.

The major conditions the mine personnel felt were necessary for efficient use of the bucket wheel were sufficient overburden and a narrower pit. The only problems hampering this operation were a lack of material to dig and sloppy conditions in times of excessive rainfall.

CASE HISTORY MINE D

Mine D, located in southwestern Illinois, maintains and operates a Bucyrus-Erie 954-WX bucket wheel excavator. It has been in commission at this site since June of 1976. Prior to operation here, this machine had been worked at one of the company's northern Illinois mines. No reasons were stated as to why the machine was moved. Operation is on a 3 shift/day, 260 days/year schedule with a rated availability of 70%. This figure includes all mechanical/electrical and operational delays.

The wheel is used to remove the 20-60 feet of glacial till with the spoil being directly cast across the pit. Remaining overburden is primarily shale ranging in thickness from 0-20 feet. This material is removed with an 80 cu. yd. Marion 5860 stripping shovel.

Blasting is required prior to excavation of the shale by the shovel. ANFO is the primary blasting agent utilizing non-electrical blasting caps and primacord for detonation. Twenty-eight foot center spacings with a 27 millisecond delay between shots are maintained. A Robins 9 1/8" horizontal drill, sitting on the coal, is used for overburden preparation. Only the shale is shot prior to excavation.

This machine has nine 7/8 cu. yd. buckets mounted on a 22½ foot diameter wheel. Under a full load, the wheel can attain a speed

of 5 3/4 rpm with 85% average fill factor. The wheel is driven by one Ward-Leonard 187½ hp motor with three gear reductions - 2 spur, and 1 herringbone. For protection, a rubber cushion is mounted on the intermediate shaft and a Fawick clutch is mounted at the motor. The maximum cutting radius from the centerline of rotation is 132 feet with the maximum digging height, when the ladder is at 12° extension, rated at 88 feet.

Both the digging and stacker conveyor bells use 54 inch wide rubber belting with replacement on an as-needed basis. The digging ladder conveyor is 77 feet long and suspended on two sets of 8 part tackle blocks. Speed can vary from 600-800 fpm, depending on the type of material being excavated. The stacking ladder conveyor runs from 800-1000 fpm and has inclination capabilities up to 15°. The main structure is mounted on four 3 foot caterpillar treads with a total effective bearing area of 384 square feet. Normal tramming speed is 0.25 mph.

Several modifications were necessary for utilization of the BWE at this mine. A 12 foot section was added to the main structure to increase the digging height and the digging and stacking ladders were extended 7 and 20 feet respectively.

Major constraints to BWE utilization are as follows:

- 1) Due to the nature of the overburden, when freezing conditions exist, the buckets tend to clog. This situation was resolved when chain mats were installed on the back of the buckets.
- 2) Isolated boulders were also a problem especially if one managed to become lodged on the digging belt. This situation caused downtime until the boulder could be removed. In addition, when a boulder too large for excavation by the BWE was encountered in the bank material, it necessitated use of a dozer to dislodge and push it to the shovel for removal.
- 3) The major problem the mine experienced using the BWE was an insufficient amount of material to be removed in certain areas. However, when the overburden was deep enough, the mine personnel felt it was a very beneficial and capable machine.

CASE HISTORY MINE E

Located in north central Illinois, Mine E operates a Bucyrus-Erie 1054-WX bucket wheel excavator. It was purchased from the Peabody Coal Company in 1970 and had been commissioned at the River King #6 Mine in southern Illinois before coming here. Due to the lack of material minable by a BWE, this machine has been out of operation since April of 1976. It is anticipated that operation will resume sometime in January of 1979. The BWE is used to remove the top 20-30 feet of glacial material with the spoil being directly cast across the pit. Remaining overburden overlying the coal is comprised mainly of shale ranging in thickness from 55-80 feet, which is removed using a 65 cu. yd. Marion 5761 stripping shovel. The seam being mined is the #6 (Herrin) coal. It is approximately 4 feet thick, gently rolling and dipping slightly to the south.

Horizontal drills, sitting on the coal, are used to prepare the overburden for shooting which is accomplished using pneumatically loaded ANFO and blasting caps. It must be emphasized that the BWE material is not shot prior to excavation.

The BWE has nine 1 cu. yd. buckets mounted on a 24 foot diameter wheel. The wheel is driven by one direct current motor with 250 and 500 horsepower attainable at 230 and 460 volts respectively. Maxi-

maximum cutting radius from the centerline of rotation is 137 feet with the maximum cutting height above the seam rated at 100 feet. Both the digging and stacker belts use 54 inch wide rubber belting with replacement on an as-needed basis. The digging ladder conveyor runs at 900 fpm and the stacker ladder conveyor runs at 1000 fpm with both conveyors having inclination capabilities up to 15° . The main structure is mounted on 3 foot 6 inch wide caterpillar tread arranged into a four double crawler assembly with a total effective bearing area of 480 square feet. The working weight excluding belting is approximately 3.2×10^6 lbs. with a normal tramming speed of 0.16 mph. This machine has a crowd capable of 45 feet when fully extended.

A three man crew consisting of an operator, oiler, and ground-man were necessary for efficient operation. The following problems limited BWE utilization at this site:

- 1) Since the bucket wheel and shovel both work on the pit floor, there was trouble with passing while in a narrow portion of the pit. This was simply resolved by widening the pit in these areas.
- 2) The machine is physically limited to excavating a maximum 100 feet of overburden. This was seldom a problem since the glacial material rarely exceeded 30 feet.

- 3) As mentioned earlier, due to insufficient material the BWE has been unable to work. This problem will be resolved when the mine plan changes and ample material becomes available for excavation.

CASE HISTORY MINE F

Mine F, located in north central Illinois, operates a United Electric Kolbe W-4 bucket wheel excavator. It has been in production since January 1, 1959. Operation is on a 3 shift/day schedule.

The BWE is used to remove 55 feet of unconsolidated glacial till with the spoil directly cast across the pit. Topsoil is also replaced with the wheel. Dozers push the stockpiled topsoil to the wheel for handling by cross pit conveyance, thus eliminating the use of scrapers.

The BWE works in conjunction with a stripping shovel. The shovel removes the remaining 55-60 feet of shale and sandstone. The seam being mined is the #5 (Springfield) coal, which is approximately 4½-6 feet thick, uniform and relatively flat.

As it now operates, profile dimensions are 415 feet in length, from bucket to discharge point, and 120 feet in height. The bucket wheel assembly is mounted on a 1928 Marion 5600 shovel frame. A 30 foot diameter bucket wheel, with ten 2 cu. yd. buckets mounted at the end of a 158 foot cutting boom is driven at a speed of 6-8 rpm by one 1000 horsepower motor. The machine has a digging range of 100 feet above the seam. Each bucket has 6 ESCO 12E inverted T teeth arranged in an evenly spaced pattern. Precutters are not used. Tooth and belting replacement are on an as-needed basis. The buckets are chain and rubber

mat backed to facilitate easier unloading.

This wheel is capable of 3000 cu. yd./hour, however, it rarely exceeds 2200 cu. yd./hour. Stacker and ladder belts are rated at 1250 and 1150 fpm respectively. The machine has a crowd capacity of 60 feet when fully extended. Several innovations were added. For example, I beams were used in place of angle irons for greater structural stability, and a belt drive system was used instead of direct drive to reduce damage due to shock loading. To eliminate bolt shear due to stress, neoprene pads were installed. To aid in maintenance, four cranes were built at selected points directly onto the BWE.

The operators have considered varying the speed of the stacker belt so as to throw the spoil material more evenly rather than just stacking it, thus eliminating the use of dozers for spreading. It was also mentioned that "by using the teeth they use and cutting down on 15% horsepower, they increase productivity by 15%". Mine F engineers have experimented with a stress gauge that employed driving a modified torque wrench into the overburden and measuring the amount of force necessary to break it free. These tests were to establish some values for cutting resistance and to be used as a means of determining the applicability of the BWE in future areas.

CASE HISTORY MINE G

Mine G, located in northeastern Wyoming, is a typical western open pit thick seam coal mine. It is a truck-shovel haulback operation utilizing 23 cu. yd. stripping shovels, 40 cu. yd. coal loading shovels, and 120 ton capacity rear dump haulage trucks. The coal being mined is part of the Smith and Roland Seam.

For a period of one year a shovel was utilized to remove overburden. Because the shovel did not encounter any rocks, management decided to switch to a bucket wheel excavator for overburden removal. The BWE employed is a modified version of the MX 3000 manufactured by Mechanical Excavators Inc. Attached to the end of the 32.5 foot wheel boom is a 24 foot diameter bucket wheel which utilizes eight 2.0 cu. yd. buckets. Theoretical production is 3500 bank cubic yards per hour in average material. The non-slewable discharge boom is 50 feet long and used 84 inch wide conveyor belting. The MX 3000 BWE has an overall length of 95 feet and a ground bearing pressure of 22.5 psi. Drive power for the unit is derived from two 400 kilowatt generators that operate as motors. German patent DBP 1484716 was awarded to Mechanical Excavators Inc. for the design of their bucket wheel position which is set at 25° angle to the axis of the wheel boom in the horizontal plane. This BWE had been originally designed as a reclaimer

which required structural changes to facilitate the stripping of overburden. Despite the objections of the manufacturer, mine management decided to implement the design changes. These changes included: increasing the bucket size from 1.5 cu. yd. to 2.0 cu. yd., and changing the power system from diesel-electric with truck convertor system to a dc drive system.

Upon implementation of the BWE in overburden, rubble rocks which would not pass through the 2.0 cu. yd. buckets were encountered in a band ranging from 500 to 1000 feet wide. To overcome this problem, large fins were fitted on the underside of the buckets with the idea that the fins would restrict the size of material that could enter the buckets. However, this idea was not very effective so a program of fragmentation of the overburden through a regular blasting program was implemented. The blasting program was not very successful, mainly because it had no effect on the widely spaced boulders which were being encountered.

The BWE was then moved to cutting unshot coal. The machine could not cut the coal quickly and efficiently enough so it was transferred to a coal loading function in shot coal. As a coal loader, two major problem areas arose. First, the coal seam was 60 to 70 feet thick and a 35 foot cut was required for the first lift. Due to the BWE's limited

vertical mobility, it could not handle this amount of undercutting. Second, the mine changed from 85 ton haul trucks to 120 ton haul trucks. It took too long to load the larger 120 ton haul trucks. Also, because of their size, it was difficult to load the 120 ton trucks side by side as had previously been done with the 35 ton trucks. Side by side loading was necessary because the BWE discharge belt was locked in place and could not be slewed horizontally. The 120 ton trucks had to be loaded sequentially which resulted in BWE downtime between trucks.

As previously mentioned, many of the problems encountered were due to the fact that the BWE was diverted from its original design function as a reclaimer. For example:

- 1) The undercarriage was not strong enough to handle the stresses encountered while digging clays and several times individual crawler sections dislodged. Also, damage to the drive line mechanism occurred while the BWE was removing overburden. A torque limiter was tried with some success.

- 2) The horizontal slew speed of the wheel boom was acceptable, but the cable-operated vertical slew was too slow for effective loading. The stacker belt had only two positions: horizontal and about 10° from horizontal.

- 3) Due to severe winters, problems with the hydraulic system freezing up were common. To alleviate this situation Vickers Engineers

moved the main reservoirs and pumps inside where heaters prevented freezing,

4) Perhaps the biggest operating problem came in finding a suitable belt that would not get cut and torn while in use. During the 1700 operating hours that the BWE actually worked, three belts were used. Unlike some other operations visited, no problems were encountered with material sticking to the belt system. To aid the existing slope sheet, belt rollers were installed to improve bucket wheel discharge.

5) Finally, there was a dust problem when the bucket wheel was working in coal. The dust could have been suppressed using sprays located at the bucket wheel, however, the water from the sprays would have frozen at the coal face during the cold Wyoming winters.

Mine G could not find a suitable application for its modified MX 3000 BWE during its 1700 hours of operation. Problems arose because the machine was misapplied from its original design function as a reclaimer.

The MX 3000 BWE could be used as a coal loader in shot coal at mines not having a thick coal seam with either smaller coal haulage trucks or a conveyor haulage system.

CASE HISTORY MINE H

Mine H, located in southwestern Washington, is an area of moderate temperatures and high winter/low summer rainfall. Local ground cover is a mixture of trees on the slopes and grass covered valley floors. Trees are removed by a commercial logger, and grubbing is used to remove the remaining plant material. Topsoil is removed and stockpiled by scrapers.

The mine operates a Demag-Lauchhammer designed cell-less bucket wheel excavator, SchRs $\frac{1940}{0.5} - 14$, which was originally built in conjunction with McDowell-Wellman for construction of the Oroville, California earthen dam. It was originally built in 1962 and commissioned at this operation in 1971. In 1964 the purchase price was estimated at $\$1.5 \times 10^6$. Operation is on a 2 shift/day, 5 day/week basis with a rated availability of 87%.

This machine is utilized to remove clay-gravel or sandy overburden in three 35 to 40 foot deep benches before final stripping by scrapers and dragline. At present, the bucket wheel excavator is working near the end of a series of 2000 foot long cuts feeding overburden to a mobile belt wagon and conveyor system which transports the material about 9000 feet to a spoil stacker across the 5000 foot wide pit.

The bucket wheel excavator is used for the less consolidated

overburden layers which are distinctly stratified. The uppermost consisting of about 35 to 40 feet of clay-gravel mixed irregularly. Beneath this the grey sandy Logan Hill Formation is distinct but loose enough not to impede the bucket wheel. Both types of overburden are free from sharp variations in hardness or buried boulders. The Logan Hill Formation is very abrasive and bucket tooth wear is a factor when working in it. Blasting of the overburden is not required.

As it now operates, profile dimensions are 124 feet in length, from bucket to discharge point, and 44 feet in height. At a weight of 1.34×10^6 lbs., it exerts a ground bearing pressure of 21.5 psi as mounted on two 56 inch wide crawlers. The crawlers are electrically driven by two 90 horsepower motors and can travel at 19.5 fpm. A 29.5 foot diameter bucket wheel, with eight 1.8 cu. yd. buckets, mounted at the end of a 61 foot cutting boom is driven at speeds variable from 4.3 to 11.6 rpm by two 400 horsepower motors. In the overburden at this site normal operating speed is 5.5 rpm with 44 bucket discharges per minute. Operators estimate a 90% individual bucket fill factor. This machine is capable of a 360° slew at 0.2 rpm driven by three 10 horsepower 460 volt motors. As it is now set up, the machine can dig 35 feet above and 1.75 feet below its crawler level. Each bucket has 8 wedge shaped ESCO teeth arranged 2 on each side, 1 corner and 3 front. Pre-

cutters are not used. Tooth replacement is individual as needed. The buckets are chain backed since the clay material is sticky. The theoretical output of the machine is variable from 2600 to 7100 cu. yd./hour based on the speed of the wheel. At the present location the output, in the more difficult digging conditions, is 1300 to 1400 cu. yd./hour. Due to slope stability considerations, the excavator is only used to take a 75 foot wide cut even though it is capable of taking a cut 150 feet wide.

In its present capacity the bucket wheel has proved to be a success and the mine management and maintenance personnel are pleased with its performance. No serious maintenance difficulties attributable to machine design or configuration were reported. Major difficulties encountered have been with the properties of the overburden and its behavior after it enters the excavator-conveyor system.

The cross-pit conveyor system is based on 9000 feet of 60 inch wide belt moving at 1000 fpm. This system is fed from the bucket wheel discharge boom, using 72 inch wide belting at 560 fpm. This, in turn, discharges to a self propelled belt wagon, with a 54 inch belt operating at 850 fpm. Finally, the belt wagon discharges to the main conveyor system. At the reclamation area the conveyor transfers spoil to a mobile stacker unit which distributes spoil preparatory to regrading by D-9 bulldozers. All conveyor belting is 2 inch thick steel cable and

rubber with idlers troughed at 35°. Life of the belting is reported to be 2 years and the belt conveyor system is satisfactory except for slippage when starting in wet weather. The major problem is cleaning sticky overburden from the belts. No satisfactory belt cleaners have been devised. At present, nylon wipers are in use. A recent experiment with a Mobil chemical product sprayed on the belts to reduce sticking is reported to be non-effective. Individual conveyor units are moved with a conveyor transverse boom system attached to a D-9 bulldozer which moves sections 2 feet laterally at each pass.

One major modification of the system has been the replacement of the bucket wheel's original steel slope sheet with a low friction Teflon sheet 1.5 inches thick. This has increased slope sheet life and reduced sticking at this point. Since this mine has a large maintenance establishment, they have, when necessary, replaced parts with on-site fabricated parts rather than order them from the manufacturers in Germany. Some parts (none were mentioned specifically) still are obtained only from Demag. Preventive maintenance is performed on weekends because the excavator only works on a 5 day per week schedule.

Mine personnel most acquainted with the bucket wheel excavator offered the following improvement possibilities:

Larger discharge and feed booms would increase the machine's flexibility and a higher power, heavier drive

system on the bucket wheel would increase the machine's digging ability.

CASE HISTORY MINE I

Located in central North Dakota, Mine I unsuccessfully operated a Demag-Lauchhammer SchRs $\frac{1000}{3}$ - 25. It was erected in the Fall of 1965 and used until the Fall of 1968 when it was dismantled for shipping to one of the company's Northern Illinois mine sites. Three separate seams of lignite (upper seam 2-3 feet, middle seam 3-4 feet, lower seam 8 feet) were mined at this site. All overburden was removed by the BWE and cast directly across the pit. The upper two seams were excavated by the BWE as they were exposed, and the lignite cast onto the pit floor where it was loaded by the electric shovel. Normal overburden and the two upper seams did not require blasting. The lowest seam was shot to facilitate shovel loading operations.

As the mine developed, ledgerrock was encountered in the BWE's working face. This ledgerrock is a hard, fine grained sandstone approximately 4-5 feet thick and lenticular in occurrence. The final rock encountered, that necessitated a change in the mining system, was about 10 feet thick and 100 feet long. For the most part, these rocks were not defined by the drilling program, even when drilling on 300 foot centers. A company mining engineer explained that normally they do not use a rock bit for exploratory drilling and pull off the hole

and relocate if rock is encountered.

In addition to the ledgerrock, rocks and boulders of varying sizes were dispersed through the overburden. These were not as troublesome as the ledgerrock, but did present operational problems. Boulders that were observed appeared to be granitic, fluvial deposits. There appeared to be higher concentrations of both ledgerrock and loose rock in the area where the BWE was applied than in other areas of the mine property.

The BWE had eight 1.75 cubic yard buckets on the wheel with a maximum speed of 9 rpm. Due to the severity of winter, an oil torch was used to prevent material from freezing in the buckets. In addition, electric strip heaters were incorporated onto the slope sheets to eliminate backup and congestion of frozen material in the annular ring. Under ideal conditions the BWE moved 3400 + cubic yards per hour with an average productivity over its operating life of 1200-1300 cubic yards per hour. It was felt that this BWE had the same productivity as a 40 cubic yard dragline. The BWE's ability to selectively remove overburden and mine the upper seams was a major consideration in selecting this machine.

The unit was equipped with D.C. drives and electric clutches. One additional problem was the angle from the motor mounts to the

drive units. Under shock loading, universal joint and clutch damage frequently resulted.

Once the continuous occurrence of the rock was determined, precutters were put on the wheel, and they helped alleviate some of the cutting problems. The precutters enabled them to mill the ledge-rock encountered. Each bucket had 6 teeth and under abrasive, milling conditions each set could require replacement after 8 hours of use. Teeth were solid and not easily replaced. As isolated rocks were encountered, the procedure was to back up, swing the boom to look at the face, and try to ease out the rock by selective cutting. Whenever possible, D-9 dozers were used to rip the ledgerock lenses and push the ripped material over the highwall where it could be removed.

Spoil haulage functioned with a double belt system on the intermediate and spoil conveyors. This was designed so that the lower belt picked up material falling from the upper belt. None of the belt cleaners tried were effective enough to totally clean the belt. Under wet conditions it often took 3 men to shovel the material stacking up on the machine. Belt alignment was also a problem in high winds, but this was an infrequent occurrence.

A three man crew consisting of an operator, oiler, and ground-man were necessary for efficient operation. However, it was generally

felt that a larger crew might have been more desirable. Both major and potential problems hampering use of the BWE are as follows:

1) The machine was very dusty to operate. A dust filter system had to be put on the blowers used to cool the motors. In general, to alleviate this problem, filters should have been placed on all openings or a positive, dust free air pressure applied to all enclosed areas to keep dust out.

2) Due to the number of components in motion, a high inertial load is experienced. A dragline usually has 7 main motors but this BWE had 25 + main motors and 7 smaller ones.

3) Due to extended downtime and high repair costs, it was felt that other stripping equipment could replace the BWE. In time, a BE 1250, 33 cubic yard dragline was put into operation.

4) Most of the problems encountered occurred when rocks passed through the buckets onto the belting, they would tend to bounce and cause damage by:

- bouncing from the belt and bending the structural members of the conveyor frame
- ricocheting off the structure and either flying into the pit or striking the belt and ruining it
- getting lodged in the structural members, ledgerrock fragments tend to have sharp edges and would slice up the belt where they touched it

5) It was felt that if BWE had all ac motors, it would have been helpful to "step start" the motors and give better speed control.

CASE HISTORY MINE J

Mine J, located in central North Dakota, produces one million tons of lignite per year. The lignite seam averages 10 feet thick and is overlain by 40 to 80 feet of overburden.

Mine J is a typical dragline direct cast area operation. It is mining a nearly flat-lying seam in an area of low rolling grass covered hills. Overburden is stripped by a 28 cubic yard dragline. Lignite is loaded by a 10 cubic yard power shovel into either 120 ton capacity Dart bottom dump haul trucks, or 60 ton capacity Caterpillar bottom dump haul trucks. Reclamation and support equipment include 2 scrapers, a Caterpillar 834 rubber-tired dozer and a Fiat-Allis HD-41B crawler dozer. A Komatsu 455 bulldozer is being tested for possible future purchase.

The bucket wheel excavator, for demonstration and testing only, at Mine J was a Barber-Greene Model WL-50 excavator. It has an overall length of 52' 1" and its three point crawler suspension system exerts a bearing pressure of 23 psi. The side-mounted digging wheel has a diameter of 16 feet and is 10 feet wide. Twelve one yard capacity buckets are evenly spaced around the circumference of the wheel. The wheel has digging speeds of 5 and 6 rpm as an excavator, and can be set up for four digging speeds as a reclaimer.

A Caterpillar 575 hp turbocharged diesel engine powers the unit. It is capable of speeds varying from 0 to 2.4 mph in either forward or reverse. Crawler drive is provided by individual hydrostatic drive motors. The front crawler is rotated hydraulically to steer the machine.

An angled dozer blade is mounted ahead of the forward end of the front crawler track assembly to clear and level the area immediately ahead of it. This small blade deposits the material in a windrow which is picked up by another angle blade located under the center of the machine. This blade directs the windrow into the bucket wheel, thereby leaving behind a smooth and clean path.

The excavator utilized three conveyors to cast the material 60 to 65 feet away from the cut. The #1 conveyor is 16'8" long, and has 54" belting moving at 950 feet per minute. It transfers material from the bucket wheel discharge to the main #2 conveyor. The #2 conveyor is 31' long and has 60" belting moving at 1000 fpm. The #2 conveyor discharge height can be controlled hydraulically. Material can be discharged, either from the end of #2 conveyor into a haul unit, or transferred to the #3 conveyor which can load another haul unit. This option permits side by side loading of haul units. The #3 conveyor is 10' long and has 60" belting moving at 1100 fpm.

The machine requires a 3 to 4 foot vertically measured cut in order to maintain maximum production. Efficient cutting is attained bank heights ranging from 4 to 16 feet with 12 to 13 feet being the range for optimal production. Through the manipulation of wheel rpm and forward speed, optimal production can be achieved for a specific material type.

Initially the machine was utilized in the excavation of unshot coal. It was reported that 1400 to 1500 tons of unshot coal could be loaded continuously in one hour. This is about twice the 700 to 800 tons of shot coal that could be loaded by the 10 yard shovel in one hour. Due to the milling action of the wheel, the excavated coal was reportedly free of large lumps and was of a consistent size. A 120 ton capacity coal haul truck could be loaded in 4 1/2 to 4 3/4 minutes according to Barber-Greene project engineers.

The BWE was next used as a spoil pile reclaimer for a week. It was put to work in spoil piles that had been standing for one year. A dozer cut a ramp from the bottom of a spoil pile to a point half-way up the slope. From here a 20 foot wide bench was constructed for the excavator to begin its cut. The machine then began cutting into the spoil bank slope casting the material down into the valley separating the spoil piles. After several cuts and some dozer cleanup work, a level spoil area resulted.

In the third week of the demonstration, the BWE excavated overburden. The machine was observed cutting up to 16 feet of overburden consisting of clay interspersed with lignitic layers and isolated petrified tree stumps. Material from the overburden cuts was deposited on the bench as windrows. These windrows were rehandled and moved further yet from the original cut. After 3 to 4 passes the material was cast over the highwall. This, of course, was only done to demonstrate the applicability of the machine to overburden excavation and was not a proposed overburden removal method. This Barber-Greene unit reportedly was capable of excavating 3000 tons of overburden per hour. Using a weight density factor of 1.5 tons per cubic yard, the machine was moving 2000 bank cubic yards per hour.

While being observed, the machine excavated overburden well, leaving a smooth vertical wall behind which occasionally sloughed. Rocks and clay lumps too large to pass through the bucket openings were carried over and deposited on the pit floor directly behind the wheel. The result of these carryover materials was a continuous trail of material at the toe of the cut, which was picked up again by the wheel on the next cut. When the machine encounters a very large rock, it must back up, move around it, and begin cutting again ahead of the large rock.

This BWE was observed rehandling in an approximately 800 foot long overburden windrow. During the 34 minutes required to make one pass through the windrow, the tons per minute moved was recorded. Under these conditions an average excavation rate of 47.6 tons per minute was measured, with a standard deviation of 3.6 tons per minute. The number of tons moved per minute ranged from a low of 40 to a high of 55. The 40 tons per minute was recorded in the initial cut where the windrow height was below the 3 to 4 feet needed for maximum production. Multiplying the average 47.6 tons per minute rate of excavation by 60 minutes yields a theoretical hourly production rate of 2856 tons per hour. This hourly production rate figure does not include any allowances for downtime due to the machine backing up. As it is designed, with the wheel on one side, it must be deadheaded in reverse to resume its initial position at the beginning of the next cut.

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PRODUCTIVITY ANALYSIS

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PRODUCTIVITY ANALYSIS

Productivity in its broadest sense refers to a rate at which a certain individual or machine makes contributions to effect production. For the purpose of this analysis, BWE productivity will be measured in cubic yards per hour. This figure is a function of the following variables:

Bucket Capacity (B_C) – The theoretical capacity of each bucket as provided by the manufacturer. It is expressed in cubic yards.

Bucket Fill Factor (f_B) – A ratio of the actual volume of material excavated by each bucket to the theoretical bucket capacity (B_C).

Number of Buckets (n) – The number of individual buckets located around the circumference of the bucket wheel.

Angular Velocity (W_r) – The number of revolutions made by the bucket wheel per unit of time, which also accounts for cutting resistance experienced by the BWE. For this analysis, revolutions per hour will be used.

Operating Time (t_o) – The actual number of hours that the BWE is operating. This figure will only be used in determining productivity for a time period other than an hour.

Functional relationships of these variables can be expressed

in the following equation:

$$P = (B_c \times f_B \times n) W_r$$

or

$$P = (B_c \times f_B \times n) W_r \times t_o \quad \text{(To convert units of time)}$$

Information contained in Table 1 and Figure 4 delineates the type and age of each BWE observed along with operating parameters for each unit. Percentages were used in Figure 4 to offset the variations in BWE size and number of operating days per year. For each BWE the actual productivity was calculated along with productivity at 85% machine availability to show realizable increases in production for corresponding increases in machine availability.

Detailed availability/downtime statistics were available for 4 BWE's. Information was dichotomized into mechanical-electrical downtime and operational downtime. These data are presented in Figure 5 through Figure 10. Figures 5, 7 and 9 relate individual downtime statistics to an overall category (mechanical-electrical or operational downtime) as a percentage of that category. Figures 6, 8 and 10 relate those same statistics to total downtime as a number of shifts¹ per year lost. By presenting the data in this fashion, it becomes immediately

¹One shift = 8 hours for BWE 1, 3 and 4
One shift = 7.25 hours for BWE 2

TABLE 1
BWE PRODUCTIVITY DATA

BWE NO. 1 (First commissioned 1963)

Availability	55%
Days/Year	362
Shifts/Day	3
Hours/Shift	8
1977 Productivity	814 cubic yards/hour
@ 55% availability	3,900,000 cubic yards/year
@ 85% availability	6,000,000 cubic yards/year

BWE NO. 2 (First commissioned - N/A)

Availability	60%
Days/Year	260
Shifts/Day	3
Hours/Shift	8
1977 Productivity	1,500 - cubic yards/hour
@ 60% availability	6,000,000 cubic yards/year
@ 88% availability	7,500,000 cubic yards/year

BWE NO. 3 (First commissioned 1954)

Availability	70%
Days/Year	260
Shifts/Day	3
Hours/Shift	7.25
1977 Productivity	690 cubic yards/hour
@ 70% availability	2,700,000
@ 85% availability	3,300,000

TABLE 1 (Cont'd)
BWE PRODUCTIVITY DATA

BWE NO. 4 (First commissioned 1960)

Availability	35%
Days/Year	360
Shifts/Day	3
Hours/Shifts	8
1975 Productivity	810 cubic yards/hour
@ 35% availability	2,450,000 cubic yards/year
@ 85% availability	5,950,000 cubic yards/year

BWE NO. 5 (First commissioned 1969)

Availability	50%
Days/Year	350
Shifts/Day	3
Hours/Shift	8
1977 Productivity	1,250,000 cubic yards/month
@ 50% availability	15,000,000 cubic yards/year
@ 85% availability	18,000,000 cubic yards/year

BWE NO. 6 (First commissioned 1959)

Availability	85% (assumed)
Days/Year	260
Shifts/Day	3
Hours/Shift	8
1977 Productivity	2,200 cubic yards/hour
@ 85% availability	11,700,000 cubic yards/year

TABLE 1 (Cont'd)
BWE PRODUCTIVITY DATA

BWE NO. 7 (First commissioned 1962)

Availability	87%
Days/Year	260
Shifts/Day	2
Hours/Shift	8
1977 Productivity	1,700 cubic yards/hour
@ 87% availability	0,150,000 cubic yards/year

BWE NO. 8 (EXPERIMENTAL)

Availability	85% (assumed)
Days/Year	260 (assumed)
Shifts/Day	3 (assumed)
Hours/Shift	8 (assumed)
Productivity	2,000 cubic yards/hour (assumed)
10,600,000 (assumed)	
cubic yards/year	

BWE NO. 9 (First commissioned 1967)

Availability	60%
Days/Year	260
Shifts/Day	3
Hours/Shift	8
Productivity	3,200 cubic yards/hour (assumed)
@ 60% availability	12,000,000 cubic yards/year
@ 85% availability	17,000,000 cubic yards/year

**BUCKET WHEEL EXCAVATOR
AVAILABILITY/OVERBURDEN PRODUCTION**

FIGURE 4

obvious where major downtime elements are located. Figures for BWE No. 4 appear on separate graphs because different delay categories were defined at that mine site. Delays are defined as follows.

BWE MECHANICAL - ELECTRICAL DELAY

Certain mechanical and electrical devices contribute significantly to BWE downtime. Following is a list of those devices as they appear in Figures 5 through 10 along with a brief description of related problems.

Cable changes - Deals with changing worn out or damaged electrical cables and hoisting cables. This combination was used to be consistent with information received from the mine operators.

Boom - Refers to the rewelding of the walkways, protective structures and structural members of the ladder and stacker booms. Rewelding of the boom area occurs because of vibration the BWE encounters while excavating. Also, damage to structural members occurs when large boulders are carried by the belt system.

Buckets - The buckets on a bucket wheel have to be repaired, maintained and even replaced much like the bucket on a dragline or shovel. This category includes the changes of the bucket teeth which occur because of wear while digging.

BUCKET WHEEL EXCAVATOR MECHANICAL-ELECTRICAL DELAYS

FIGURE 5

Hoist – Refers to maintenance and downtime associated with the hoist motors and systems which enable the bucket wheel to be moved (hoisted) vertically along the digging face.

Swing – Refers to maintenance and repair associated with the swing motors. These motors enable the bucket wheel and ladder boom to be moved horizontally across the working face.

Crowd or Drag – Refers to maintenance and downtime associated with the crowd mechanism. Crowding allows the bucket wheel to be thrust into and retracted from the working face without any movement of the BWE on its tracks. The entire end of the ladder boom containing the bucket wheel rides on a rail or gearing system which is driven by the crowd mechanism.

Propel – Refers to maintenance and downtime associated with the propel motors which control the crawlers and ultimately control movement of the BWE as a complete unit. When the propel motors are down the BWE cannot move.

Crawlers – Refers to care, maintenance, and downtime associated with the crawlers and the crawler assembly. Worn out or damaged pads and sprockets must be replaced for continued mobility.

Belts – Maintenance and replacement of belts worn or damaged through normal usage or contact with large boulders and sharp rocks.

**BUCKET WHEEL EXCAVATOR
MECHANICAL-ELECTRICAL DELAYS**

FIGURE 6

Further, all other items associated with the conveyor belting system such as the idlers and idler pins are included. Belts are located throughout the entire length of a BWE; from the bucket wheel through the ladder boom, transfer point, and through the discharge boom.

Service - Refers to regularly scheduled maintenance items such as replacement and changing of lubricants, antifreezes, lightbulbs, safety equipment, etc. Also included are engine tune-ups.

Other - All other miscellaneous mechanical-electrical delays not associated with an aforementioned delay category are placed in the "other" delay category.

BWE OPERATIONAL DELAYS

Items not associated with mechanical and electrical devices were also major contributors to machine downtime. These items are grouped into BWE operational delays. The following is a description of these delays as they appear in Figures 5 through 10.

Change Cables - Refers to the large high voltage cables that run from the BWE to its external power source. Often cables between the BWE and shovel will be interchanged with the unit needing the most cable borrowing from the other unit. During blasting the BWE's cable sometimes must be moved to protect it from the blast.

BUCKET WHEEL EXCAVATOR OPERATIONAL DELAYS

FIGURE 7

Cleaning Pit - Refers to making a few passes with a dozer to cleanup the pit bottom area in which the BWE must work for the next shift. Cleanup is needed for small and major highwall sloughs and avalanches. Also, cleanup is required after a large shot involving a great deal of flyrock.

Move Up - Time actually spent in moving the BWE to the working face. Should be a very small delay except in cases where the BWE may be shutdown for a long period of time and has to move a long distance to the new active working face after being reactivated. Also, involves moving from an old pit to a new one.

Deadhead - Once a BWE completes its cut along the entire length of a pit, it has to be deadheaded or moved back along the entire length of the pit to the opposite end, the point from which the previous cut began. During deadheading, the BWE is not digging and production is at a standstill.

Pass Machines - When either the shovel or BWE is deadheaded in a tandem stripping operation, there is usually a delay at the point where the two machines must pass each other. In some mines, the pit is so narrow that the two machines cannot pass without first excavating a wider than normal cut.

No Spoil Room - In cases where the spoil area is already filled in too high by other excavation, adding more spoil would make it even

BUCKET WHEEL EXCAVATOR OPERATIONAL DELAYS

FIGURE 8

harder to approximate original contour at the time of reclamation.

Flooding - During periods of high precipitation, flooding, of course, can occur, requiring a BWE to be shut down until the water can either be drained by ditches or pumped from the pit area.

Clean Dirt - New safety regulations require all equipment to be kept clean and free of dirt as much as is possible. Especially susceptible are the bucket wheel area and the transfer point between the ladder and discharge booms. The entire belt system also requires a great deal of cleaning.

Other - Includes all operational delays not associated with the aforementioned delays. However, the large majority of "other" operational delay time can be attributed to periods of time during which the BWE is shut down completely due to the fact that it has caught up with the shovel and has no overburden to excavate. A BWE can easily catch up to a shovel because it moves a smaller volume of material than a shovel at a higher excavation rate. This is, of course, an equipment mismatch. In some cases the equipment mismatch delay is a major cause of BWE downtime.

In general, overall availability was significantly lower than expected for the four BWE's observed. Table 2 illustrates overall availability.

**MECHANICAL, ELECTRICAL & OPERATIONAL DELAYS
BUCKET WHEEL EXCAVATOR NO. 4**

FIGURE 9

TABLE 2
BWE AVAILABILITY

<u>BWE #</u>	<u>Overall Availability</u>
1	53% *
2	61% *
3	23% *
4	35% **

MEAN AVAILABILITY = 43%

* Based on 10 months of data and field survey.

** Based on 1975 data

Further analysis of downtime statistics indicates the major categories that contribute to the lack of machine availability. Table 3 indicates these downtime categories as a percent of total downtime.

TABLE 3
CATEGORY DOWNTIME AS A PERCENT OF TOTAL DOWNTIME

<u>BWE #</u>	<u>Mech.-Elec. Downtime</u>	<u>Operational Downtime</u>
1	70.6%	29.4% *
2	63.8%	36.2% *
3	21.8%	78.2% *
4	37.5%	62.5% **

* Based on 10 month data

** Based on 1975 data

It is interesting to note the swing in downtime from almost totally mechanical-electrical for BWE #1 (70.6%) to nearly all operational for BWE #3 (78.2%). This can be traced almost exclusively to differences in the type and volume of material handled by each BWE.

MECHANICAL, ELECTRICAL & OPERATIONAL DELAYS **BUCKET WHEEL EXCAVATOR NO. 4**

FIGURE 10

Major mechanical-electrical delays for BWE #1 occurred in the belts and crawlers subcategories, while belts and buckets accounted for major delays for BWE #2. In both cases, the BWE was excavating un-shot material peppered with large rocks. The presence of rock in the overburden caused mechanical failure in several ways:

1. When the bucket tooth impacts a large rock, three physical principles apply: impulse and momentum, conservation of momentum, and conservation of energy. If the smallest cross section of the tooth cannot absorb the energy generated by the impact, the tooth will fracture.

2. If the rock did find its way into the bucket, the force with which the rock was dumped onto the conveyor caused the rock to bounce down the conveying system. This caused the belt to deform under severe stress and strain, which caused the belt to weaken and eventually fail.

3. The crawler units, traveling over rock, were subjected to constant tension and compression loads. This caused fatigue failures in the grousers and retaining pins.

Major delays for BWE #3 and BWE #4 were operational. Mechanical-electrical delays were not as great a problem due to unconsolidated nature of the material excavated by the BWE. The BWE

was able to move more quickly and catch up to the excavating shovel.

This mismatch of equipment resulted in excessive delays.

To overcome such operational delays, more concentrated efforts should be placed on pre-mining planning and equipment justification analysis.

In order to increase BWE productivity, certain major issues must be addressed. Improvements in belt materials and design to increase life and facilitate ease of replacement, and development of vibration damping apparatus for conveyor systems would significantly improve mechanical-electrical availability. However, increases in mechanical-electrical availability will only tend to increase operational downtime unless good mine planning and equipment matching methods are adopted.

**MINING SYSTEM
EVALUATION AND
ANALYSIS**

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MINING SYSTEM EVALUATION AND ANALYSIS

Different methods are used in applying a BWE to the removal of overburden. The use of each method is dependent upon various internal and external factors. Figure 11 on page 84 illustrates the different mining methods currently utilized in the United States.

The following section is a discussion and comparison of the methods employed. In addition, various influences on mining systems such as overburden characterization and cutting techniques are addressed.

MINING METHODS

High-Deep Cutting

None of the successful or unsuccessful bucket wheel operations visited during this study used a high-deep mining approach. Because of this, the following discussion is theoretical and based on literature sources.

In general, the bucket wheel excavator is designed to operate by cutting benches above its crawler base level. This is the high cutting mode of excavation. In the deep cutting mode, material is excavated below the excavator's base level. Material can be deep dug usually in a ratio of 1:3 or at a maximum of 1:2 when compared to its high cut ability. There are two methods of deep cutting in use. The first utilizes a wheel

BWE MINING METHODS

FIGURE 11

rotating in the same direction in both high and deep cuts. This requires an extremely long wheel boom or boom crowd capability. The second method reverses the direction of rotation of the bucket wheel.

A primary advantage of the combined high-deep cutting method is the increased total excavating height available with this plan. In addition, in mines using movable conveyor systems and where more than one bench is being removed, both bucket wheel excavators can sit on the same bench and discharge into a common conveyor system. One bucket wheel excavator can dig high, down to the bench level; the second can dig deep while sitting on the same bench level. The common conveyor may be placed between the two excavators since both will progress in the same direction. This can eliminate duplication of equipment and simplify the mining operation.

Several disadvantages appear. The most prominent is that on wheel boom conveyors set at an angle greater than 35° to the horizontal material starts to slide on the belt. This may require either special anti-slip belting or cover belts. Each of these solutions may add maintenance and equipment expenditures to those of the machine. An additional condition which may prove disadvantageous in the future is the trend toward shorter bucket wheel booms by most manufacturers. This will tend to eliminate the single direction of rotation wheels from deep cut mining.

Although there are very few in operation, a celled or semi-celled bucket wheel cannot have its direction of rotation reversed, hence any mine contemplating a deep cut must adopt a cell-less bucket wheel excavator.

Conventional Mining Approach

One of the most often utilized bucket wheel excavator mining approaches is called the conventional approach. The general idea of this system is that the bucket wheel sits directly on the coal in the pit or on the floor of a bench in multiple bench operations. From this vantage point the BWE is capable of various extraction schemes. Two extraction methods currently in use are the terrace and dropping cuts. These will be reviewed later in the text. In all of the operations visited, conventional mining was the only method employed.

At present, one of the more practical advantages offered by the conventional approach is that the BWE can cast spoil directly across the pit, thus eliminating the use of additional equipment for spoil placement. This also indirectly reduces congestion in the working area. Another advantage is the vertical working range in which the bucket wheel can operate. Due to design features, BWE's generally have a greater working range above their crawler level. Therefore, by sitting directly in the pit, mining of higher overburden can be performed with-

out exceeding the machine's reach capabilities.

Two very distinct disadvantages are associated with mining in this fashion. First, large working pit dimensions must be maintained. This is particularly true when the BWE is working in conjunction with a power shovel. A rehandle problem is caused due to the relatively short casting distance of the shovel with respect to the BWE. A sufficiently wide pit must allow for the two very large machines to pass each other. Second, when the BWE and the shovel are well matched in their output the machines should be operating fairly close to one another. When the BWE is deadheading in preparation for its next cut, downtime of the shovel can sometimes result causing operational delays.

Terrace Cut

Full and lateral block terrace cutting are bucket wheel excavator mining methods employed in open pit coal mines in the United States. Both techniques are basically the same, however, slight variations in approach and positioning of the BWE are the differentiating factors.

In the Illinois Basin, Mines A-F utilized the lateral block cut. It was in all cases a tandem shovel-BWE operation. The bucket wheel excavated the upper unconsolidated alluvium and glacial till while the shovel removed the harder shale layers.

In using the lateral block method to facilitate movement of the bucket wheel excavator, the crawlers are placed parallel and beside the working face. This allows for maximum mobility and eliminates the need for turning the machine when advancing the pit. Generally, the area being excavated is removed in a series of terraces or benches. The width of each terrace is dependent on the swing of the horizontal arc and the length of the cutting boom. Cutting height is usually considered to be $\frac{2}{3}$ the diameter of the wheel. The mining sequence is primarily the same as the full block terrace method, except the upper cut may be exposed for a greater lateral extent prior to the start of the next lower bench.

There are several advantages offered by this mining method. Coal occurring in thin seams can be recovered by selective mining, which can account for greater productivity when compared to conventional mining techniques. Another advantage is the elimination of auxiliary overburden haulage equipment. This is achieved through direct casting of spoil materials. The most advantageous reason for this method is realized when the height of the material is such that complete excavation can be made with one cut. This eliminates the additional time spent in excavating another terrace and in movement of the BWE.

One major disadvantage is that traveling distances are much greater. Generally, the entire pit must be traversed to complete a bench. However, as mentioned earlier, if only one terrace cut is necessary then uninterrupted continuous operation can be attained.

In using the full block method, the machine crawlers are situated behind and parallel to the working face. Haulage from the working face is either by shiftable face belt conveyors with or without crawler-mounted belt wagons or direct cast. At Mine I, overburden was direct cast across the pit.

The prime advantage in utilizing this method is the amount of material that can be excavated from one position. This abrogates numerous delays due to movement and placement of the bucket wheel to excavate the lower terraces. Essentially, a complete series of cuts can be removed without machine movement.

Dropping Cut

At present, no surface coal mine in the United States uses a typical dropping cut. However, Mine H in the state of Washington uses a modified dropping cut.

Theoretically a dropping cut has several advantages under special conditions of overburden. It also has advantages in relation to conveyor

haulage systems. In hard digging using a shiftable conveyor system, the dropping cut is more efficient since it produces a smaller lump size. This reduces strain on the conveyor system, allowing a more trouble free operation. The smaller or more uniform lump size produces less strain on the belting. It also eliminates shocks at the belt transfer points. Since one major maintenance difficulty to the bucket wheel conveyor system is reported to be belt damage due to oversize, sharp edged rock fragments, the homogenization of the overburden is a positive factor of the dropping cut method. Operations with dropping cut have shown that a decreased amount of machine travel is necessary to maintain production. The third major advantage is that of better operator control over the depth of the cutting. This gives better determination of the final slope angle. In areas where cut stability is a factor, this is an important safety and productivity consideration for any mine. With a dropping cut a flatter slope is maintained, giving it more stable characteristics. Another positive effect of the operator depth control feature of the dropping cut is the relatively more uniform amount of material removed at each slice. This factor keeps a continuous supply of material in the transport mechanism at all times, improving the efficiency of that segment of the overall system.

The primary disadvantage of dropping cut is the increased

power output required when using this method of mining. A modified version of this method used at Mine H suffered some problems due to highwall undercutting which led to sloughing material falling onto the wheel from above its maximum height. This was considered acceptable by the mine personnel involved.

Dropping Cut Modifications

At Mine H, in southwestern Washington, the bucket wheel excavator is used in a modified dropping cut manner. The bucket wheel excavator, as it currently operates, has a 29.5 foot wheel diameter, but it is used to take 35 to 40 foot cuts in the overburden. Most empirical studies of bucket wheel operations have recommended a cut $\frac{2}{3}$ the wheel diameter for efficient use of the cutting arc available. For this machine it would yield a value of 19.7 feet. As it is used now, the bucket wheel undercuts the overburden in a series of dropping cuts, and the wheel at times works with its full diameter in the overburden clay/gravel. Near the bottom of the vertical component of its path through the overburden, it is only picking up loose fallen material at the base of the highwall. At these times less than $\frac{1}{3}$ of the full diameter may be in use. When sufficient support has been removed, the upper overhang sloughs off onto the bench when it is pushed up to the highwall by a D-8

dozer for pick up by the bucket wheel on the lower portion of its pass.

Advantages of this method are that it enables a fairly small, compact machine to loosen and ultimately remove material at a greater height than it can reach to dig in the normal dropping cut fashion. In the overburden encountered at this mine, sloughing from the nearly vertical highwall is relatively limited. The cohesive clay/gravel mixture sloughs off only where it has been undercut and crumbles as it falls. Since no larger blocks of tenacious stone occur, fallen material is easily handled by the bucket wheel. Some of the clay lenses may remain in blocky form but any material that falls on the wheel mechanism tends to deform and absorb or dissipate the energy of impact itself rather than transmit its full force to the machine.

Several disadvantages occur with this method. First is the requirement for a second piece of large equipment, a D-8 dozer, to operate in conjunction with the bucket wheel excavator to ensure that all the loosened material is removed. A second disadvantage was observed; when large masses of the undercut ledge fall at once, the wheel speed is drastically reduced and may be stopped. Even though the material is friable and deformable, some considerable shock is transmitted to the boom support system of the wheel. These slowdowns reduce the output efficiency of the machine. Shocks to the support system may

lead to increased maintenance costs or downtime. Neither of these two problems were specifically reported by the mine personnel, nor was any boom damage observed by the field teams.

Special Mining Approaches

A Barber-Greene WL-50 Excavator was being demonstrated in a North Dakota lignite mine for its potential in overburden and coal removal. This machine has an entirely different design from that of other manufacturers but is considered a bucket wheel excavator since it utilizes a rotating bucket wheel for digging and conveyors for transfer and discharge of excavated material. During the demonstration, the Barber-Greene WL-50 was applied to overburden removal, topsoil removal, unshot coal loading, and rehandling spoil.

Advantages of the excavator are its versatility, high continuous output, low capital cost relative to capacity and mobility. The machine was able to do each phase of its operation to the satisfaction of its operators.

In the clay/lignite overburden, the machine was reported to be capable of excavating 2000 bank cubic yards per hour. While rehandling spoil, a measured value of 1800 cubic yards per hour was recorded. During the removal of unshot lignite this BWE excavated and loaded 1500 tons per hour. Since the unit cuts by being driven directly into

the bank to be excavated, no vertical or slew motions of the bucket wheel are required. Cutting forces are developed by the wheel rotation and contact with the face is maintained by the power developed in the motive crawlers. This arrangement greatly simplifies the design of the machine and should reduce its overall maintenance requirements. As a very mobile piece of equipment the Barber-Greene WL-50 Excavator is capable of being moved rapidly from one job to another within a mine site. Because it is a continuous excavator, in a truck haul operation during coal loading, tandem truck operations are required for maximum efficiency in the system. In a system utilizing an extended conveyor system for either coal or overburden transport, the feeding of a rotating wheel excavator is an ideal match.

Another advantage is found in the side placement of the wheel itself. Boulders or other material too large to enter the bucket may be carried over the wheel and dropped on the bench behind the machine. This eliminates several problems associated with large boulders such as belt fractures and dislocation of structural members. In a conventional bucket wheel excavator this overcast material may fall and strike, with potential for damage, the wheel boom or moving mechanical parts.

Several disadvantages of the excavation plan of this machine are apparent. The fixed digging range of the WL-50 limits it to mul-

multiple benching in high overburden or thick coal seam extraction. To remove a layer of depth greater than that of the bucket wheel requires repeated passes through the material. The limited distance at which material can be cast directly (60 feet) requires that it either rehandle its own spoil or be linked to a truck haul or conveyor system. Since the unit can only dig on one side, it must deadhead back the length of the cut to begin excavation on each pass through the material. The full bucket width is also not utilized in making each cut. On the side of the bucket wheel adjacent to the machine, relatively little material is in contact with the cutting edges and teeth of the buckets. This results from the steering arrangement and the presence of loose material at the working face. A single crawler is used in front for steering. Because of the loose material at the base of the highwall, this crawler must operate at a distance several feet from the base of the wall. This means that most of the bucket wheel picks up only loose fallen material. Actual cutting is performed only by the outside edges and corners of the buckets.

COMPARISON OF EXTRACTION METHODS

The major difference between a terrace cut and a dropping cut is that the bucket wheel maintains a constant elevation, or remains level in its slewing motion throughout a terrace cut. The resulting terraces

help to stabilize the slope in much the same manner that the benches of a large open pit mine aid in pit wall slope stability. In applications of the BWE exclusively to the top layer of loose overburden material not exceeding the diameter of the bucket wheel in depth, a single terrace cut along the face will suffice. Single terrace cut was the observed BWE application in several mines visited.

The high-deep mining approach requires a large amount of overburden that can be removed by BWE's. The high-deep mining method as currently utilized involves either : one BWE equipped with a long boom cutting both above and below its bench elevation, or two BWE's discharging material into a common conveyor system. In the two BWE systems, one of the BWE's excavates material above the bench elevation using a high cut, while the other BWE excavates material below the common bench elevation. The high-deep mining approach is used only in foreign countries where the BWE minable overburden occurs in thicknesses large enough to require a combined high and deep cut in order to effectively remove the overburden.

In mines where the BWE minable overburden thickness is relatively small, a conventional terrace-cut mining approach is adopted. Such is the case in all but one of the United States BWE mining applications

where the BWE minable overburden never exceeds 60 feet thick. The exception occurs at Mine H where the BWE minable overburden is as much as 120 feet thick. Their BWE removes overburden by the conventional terrace-cut method in 40 foot benches. The undercutting that must be done at Mine H could be avoided by utilizing a high-deep mining approach. However, the high-deep mining method is not used at Mine H because its BWE is not designed to dig more than 3 feet below its crawler level.

MINING SYSTEMS INFLUENCES

As previously stated, certain internal and external factors influence overall BWE utilization. Among these are overburden characterization and cutting techniques. This section addresses both of these determinants.

Overburden Characterization

Sites Observed

Of the open pit coal mining operations in the United States utilizing bucket wheel excavators, the vast majority of successful sites are located in the Illinois basin. To facilitate explanation, the mine sites

are grouped according to the geographic province they fall within: northern or southern Illinois. A brief discussion of essential geologic background is provided and followed by a description of overburden characteristics unique to each mine. The only other operation experiencing success with a BWE is Mine H, which is located in southwestern Washington. It is treated in a section by itself.

In the Illinois basin, cyclothems provide the basic sequence of lithologic characterization. A cyclothem is described as a series of beds deposited during a single sedimentary cycle that prevailed during the Pennsylvanian Period. See Figure 12 for illustration of ideal cyclothem and characterization of its members. In all of the Illinois mines visited, the coal seams occurred in the St. David and Brereton Cyclothems which are part of the Carbondale Group of Pennsylvania Age. In all cases there are variations in the lithologic units occurring in these cyclothems.

In the northern Illinois province three mines were visited. Mine A is mining the #5 (Springfield) coal after removing approximately 90 feet of overburden. The upper 30 feet is comprised of clay and glacial till which is compact yet friable, and the remaining 60 feet consists predominately of gray shales, a 10 foot sandstone body and a shale layer with limestone partings.

LITHOLOGY

ADAPTED FROM:

Kosanke, R.M., et al. Illinois Geologic Survey of Investigation 214, 1960, PP. 84

CHARACTERISTIC CYCLOTHEM STRATIGRAPHIC SEQUENCE

FIGURE 12

Mine E is mining the #6 (Herrin) coal and removing approximately 90 feet of overburden. The upper 20 feet is comprised of loam and yellow clay. The remaining 70 feet consists predominately of gray shales, 20 feet of sandstone and 2 feet of limestone.

Mine F is mining the #5 (Springfield) coal under approximately 110 feet of overburden. The upper 53 feet is comprised of glacial till, a soft, brown sandstone and sandy clay. There also appeared to be organic material disseminated throughout this upper material. This was the only mine site using the BWE in the more consolidated materials. The lower 57 feet is a sandy shale with thin (5"-12") sandstone lenses irregularly distributed. The major similarity between these three northern Illinois mines is the shale layer which occurs lower in the overburden.

In the southern coal province of Illinois three mines were also visited. Mine B is mining the #6 (Herrin) coal and removing approximately 65 feet of overburden. The upper 20 feet is comprised of a brown, friable clay-like soil and glacial till with a lower 45 foot layer of gray shale.

Mine C is mining the #6 (Herrin) coal and removing approximately 115 feet of overburden. The upper 40 feet is primarily a brown, well lithified clay-like soil and the remaining 75 feet is interbedded shales

and limestone.

Mine D is mining the #5 (Springfield) Coal and removing approximately 105 feet of overburden. However, it averages 60 feet in most places. Therefore, the material the BWE excavates varies from 15 feet to 60 feet. It is composed of glacial drift, soft, sandy, pan and clay-like soil. The remaining overburden is comprised of shales interbedded with limestone. In the southern region there are few similarities evident between individual sites.

Mine H, located in southwestern Washington, is mining the Big Dirty Coal after excavating a maximum of 200 feet of overburden. The upper 35 to 40 feet is comprised of irregularly mixed clay and gravel and the remaining 155 to 160 feet is the Logan Hill Formation. It is a loosely consolidated gray sandstone with interbedded shale lenses. Although free from variations in hardness and buried boulders, it is very abrasive and distinctly stratified.

Unsuccessful Sites

Neither of the two unsuccessful bucket wheel excavator operations had available geologic cross sections nor were their drill core logs open for a detailed overburden analysis. In both cases, the mine had progressed beyond the area where the bucket wheel excavator was operated.

Because of this, the discussion of overburden characteristics will be very general based upon superficial field observations in the general area where the BWE operated and accounts obtained orally from cognizant mine personnel.

At the North Dakota site the overburden consisted of primarily unconsolidated clay or poorly consolidated sandy shale covered by a deep topsoil layer. This basic overburden matrix material was loose enough to be excavated directly with no blasting required. The overburden in this area of the mine property had two features which were unexpected by the mine operators and undiscovered by their premining exploration program. The first and most frequent was the occurrence of dispersed, water worn, very hard rock formations. In some cases they occurred as layers or lenses deeper than the soil horizon. In other cases they consisted of scattered rock ranging in size from cobbles to over two feet in diameter. This type of rock can be seen in the spoil of the present mine area and occasionally outcropping on the surface in the unmined area near to where the bucket wheel excavator operated.

A second geologic feature was the existence of isolated hard lenses of sandy shale or fine grained sandstone which occurred within the softer shale layers. These lenses range from very thin to over 10 feet thick and 100 feet long in the area where they were encountered by

the bucket wheel excavator. Usually they ranged from 4 to 5 feet thick. Generally, the change in cutting resistance from the softer material to the embedded boulders or sandstone lenses was significant enough to prevent full economic application of the bucket wheel excavator at this site.

At the unsuccessful Wyoming site the basic type of overburden was a loosely compacted sandy shale material with a topping of thin topsoil. In portions of the area, however, layers of isolated water worn boulders were encountered. These gravel-boulder bands contained elements too large to pass through the mouth of a 2 cubic yard bucket and were too hard to be broken by the bucket wheel excavator's teeth. These layers of boulders were up to 1000 feet in length where the bucket wheel was attempting to dig.

Demonstration Site

The overburden at the Barber-Greene demonstration lignite mine in North Dakota consists of 40 to 80 feet of clay-like shale with small interbedded layers of lignite up to 2 feet thick. At some areas within the mine the shale layers are hard and more sandy. Within the 15 foot highwall exposed by the WL-50 Excavator, there occurs a 12 to 24 inch layer of friable weathered clay. Beneath this layer lies the gray clay-

like shale which is easily cut by the bucket teeth. At one end of the cut two lignite bands occur. The upper band is 6 to 8 inches in thickness and the lower band is approximately 24 inches thick. At intervals in the upper layer there are large diameter fossilized tree stumps. A layer of shale 2 feet thick separates the upper lignite from the lower lignite layer. The remaining material visible in this cut is the common dark gray soft shale. At other sites within the mine, the gray shale is compact and hard with a tendency to fracture into thin slabs. These hard shales seem to be confined to the deeper levels of the overburden.

Problem Areas

Five problem areas related to overburden characteristics are individually identified and discussed in this report. They are approached in three groups. The first is related to hard rock occurrence in two forms, dispersed boulders and continuous rock layers. The second group, abrasive material, is related to physical characteristics and may occur in either rock or softer overburden. The third group is partially dependent upon the climate (i.e., rainfall interacting with the overburden material). These are stickiness and vegetative materials present in upper overburden layers.

In the first group, the effect of either dispersed individual boulders

or continuous rock lenses is quite similar when they are encountered in a more easily cut matrix. They generally cannot be cut by a bucket wheel when it is set in its digging mode for softer material. Thus encountering a rock of this sort unexpectedly incurs a considerable chance of damage to the bucket tooth or a shock to the wheel drive mechanism. This sudden change in cutting resistance may damage the wheel motor drive shaft or its gear train before the wheel can be stopped if the rock is struck solidly and is immovable. In either case, if a rock too large to enter the bucket is lodged in the bucket mouth it may, if carried over the wheel, be dropped on the boom, causing damage. Even if the large rock or a fragment of a consistent rock layer is dislodged or loosened it will require a separate and time consuming effort to remove it from the path of the wheel. This, if it occurs often, can result in as much lost time as a mechanical failure. The primary danger with hard rocks is based on lack of precise knowledge of their position or existence. The shock effect is the main source of damage to the wheel.

A second adverse feature of rock fragments or boulders is their behavior within the conveyor/transfer system of the bucket wheel. When sharp edges are present, belt cutting is common. Bouncing generated by the energy transferred to the rocks from the force of gravity and belt motion may either eject them from the conveyor onto the machine

superstructure or onto other equipment.

Continuous rock layers of sandstone can be cut using a high bucket wheel rotational speed, precutters and specially hardened teeth. This results in a milling action that requires the machine to be totally devoted to removing the hard rock layer. Where this is a large portion of the overburden, it becomes difficult if not possible to justify economically.

In the second overburden problem, highly abrasive material, the major equipment difficulty arises at the cutting edge of the bucket either on the teeth or the bucket lip. Overburden high in silicon dioxide, even if it is not consolidated, causes considerable abrasion of those surfaces passing through it. Frequently, in some cases as often as every eight operating hours, tooth replacement or rebuilding is necessary. Surface hardening may alleviate the problem, but requires additional expense for hardening material and manpower. Worn teeth are less efficient, requiring a greater power output per unit of material excavated than sharp teeth.

The climatically dependent overburden problems, stickiness and vegetative material, will of course, vary from one locality to the next. Clay based rocks (i.e., shales) and clay lenses interspersed in other materials are most susceptible to changes in their physical char-

acteristics when wetted. Swelling may occur with a drastic increase in bulk. Sticky clays tend to adhere to machine surfaces at any point in the bucket wheel system. Especially vulnerable are buckets, transfer or slope sheets, conveyor belts, and conveyor transfer points. On transfer or slope sheets a build up of material reduces the volume which can be quickly removed from the annular ring of the wheel and reduces outputs. Bucket fill factors can be significantly reduced by heavy layers of clay clinging to the bucket sides. Slower speeds of wheel rotation may be required to allow time for slow moving sticky material to fall from the bucket onto the annular ring. Sticky material may interfere with smooth conveyor operation if it is not removed by belt cleaners. A thick build up of clay increases the overall stress on the drive system due to the increased weight on the belting. In addition, the same problems with filling may occur at belt transfer points.

The presence of vegetative material in the upper layers of overburden may cause problems primarily due to the fibrous nature of root systems. If these are not cut by the bucket wheel teeth, they are torn out and may become twisted around the buckets or any rotating portions of the machine. These may reduce the efficiency of the excavator enough to require stopping the wheel to remove them. All these overburden related problems can, as has been shown, lead to mechanical problems

in many subsystems of the bucket wheel excavator.

Evaluation of Cutting Techniques

Several limitations arise with either crowd or crowd-less bucket wheel excavators. A crowd-less excavator must rely upon its crawlers to regulate its cutting slice thickness. This feature increases the wear on the drive and crawler system of the excavator. A series of short advances and retreats to adjust the bucket wheel to the cut depth are necessary for accurate positioning of the cut. Research into braking and smoother drive systems for the crawlers would alleviate some of the problems and reduce the wear on the track drive mechanisms. Another feature of crowd-less bucket wheel excavators in need of research is the constant output control. As a crowd-less wheel is cutting its arc into an overburden bank, its slew speed must be increased in accordance with the $\cos \varphi$ in order to keep up a constant flow of material from its cut.

$$v_{\varphi \text{ slew}}^{\text{slew}} = \frac{v_{\text{slew}}}{\cos \varphi} \text{ (m/min) where } v_{\text{slew}} = \text{the slewing speed at } \varphi = 0^\circ.$$
 This condition must be met within a maximum slew speed of 40 m/min. ($v_{\text{slew}}^{\text{max.}} < 40 \text{ m/min}$). At slewing speeds greater than 40 m/min braking forces or the potential damage from hitting an obstruction become excessive. Research into automated methods of con-

tinually varying the slewing speed should be conducted.

A bucket wheel excavator with a crowd feature has increased mechanical complexity over a crowd-less model. The flexibility of a crowding machine may be worth the potential additional maintenance problem of the crowd motors and gear trains. A simplification of the crowd control mechanism and motive force in order to make the machine less troublesome might be a useful research project. The machine with crowd capability has come into some disfavor as a trend grows toward smaller, more compact machines. With research, this useful aspect of the bucket wheel excavator might regain its position.

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OVERVIEW OF COMMON DIFFICULTIES ENCOUNTERED

Characteristics that contribute to BWE downtime can be viewed in a broad sense. Through the course of this study, it was determined that there are four broad categories into which major problems can be grouped:

1. Geological
2. Maintenance
3. Climatological
4. Mechanical

The nature of problems associated with each category is discussed in detail in the following sections.

GEOLOGICAL

In strip mining situations where bucket wheel excavators are utilized, geological considerations play a fundamental role in the determination of mining approaches. This influence in itself can be the most significant criterion of the ultimate success and sustained application of large BWE's to future mining.

Lithology and stratigraphy are two major geologic aspects that must be accounted for in determining mining approaches. Each shall be addressed separately due to the magnitude of the inherent problems that are possible, both singularly and in combination.

Lithologic factors can influence both productivity and the amount

of downtime experienced by the BWE. The nature of these problems is derived from the hardness and abrasive character of the material. Abrasiveness accounts for downtime due to excessive wear on teeth and bucket components. This can, in some instances, be offset by changing tooth shape and/or position on the bucket. However, in most cases these modifications are not significant enough to entirely eliminate the effects of wear due to abrasion.

Loss of production can in many cases be attributed to hardness or tenacity of the overburden. In either situation, power requirements must be increased so that sufficient bucket fill is accomplished. In certain instances of sticky material, however, some power reduction is necessary to allow more cohesive materials sufficient time to move from the bucket onto the conveyor for removal. More favorable for BWE excavation are unconsolidated alluvium, soil, and glacial tills. However, this by no means eliminates potential application to other materials under special conditions.

The least troublesome of these geologic considerations is the stratigraphic sequence of lithologic units of varying consistency or hardness. If the material is arranged in such a pattern that partings disrupt the continuity of the overburden it may necessitate additional excavating machinery (such as power shovels) to remove harder layers. However,

if the partings are not of considerable lateral extent, this problem may be simply resolved by adopting a selective mining plan.

Lithology and stratigraphy were of major concern at most mines. These factors were of such magnitude and extent at Mines G and I that they limited the use of the BWE. Although methods were employed to alleviate the situation, downtime and mechanical problems eventually led management to the conclusion that the machines had been misapplied.

Stratigraphy was a particular problem for the mines in the Illinois basin. Although the BWE had adequate production rates to handle all the overburden material, the hardness of the shale in the lower portion of the working face prohibited mining by the BWE. It must be emphasized that the shale could have been excavated by the BWE, but the resulting downtime for tooth replacement and failures related to severe shock loading prohibited economic utilization. Therefore, a BWE-shovel combination was necessary for efficient operation.

MAINTENANCE

The bucket wheel excavator does not differ greatly in the amount of structural maintenance required when compared with other large excavating machines such as draglines and shovels. A BWE, like any other equipment item, benefits greatly from a rigidly administered

preventive maintenance program. A major difference between shovel/dragline maintenance and BWE maintenance is the increased number of motors and the internal conveyor systems of BWE's. These factors account for most of the additional maintenance problems associated with wheel excavators.

Major downtime can result when crawlers, belts or sprockets have to be replaced on a BWE. This can be attributed to the large size and weight of BWE component parts. Maintenance on a large BWE requires heavy duty cranes and specially designed machinery to handle the associated subsystems and the massive parts.

A common problem encountered at some mines was the extended time required to obtain new parts for their German made BWE's. This problem was circumvented by one mine that had the ability to fabricate almost all of its own parts by utilizing its extensive maintenance facilities. Another mine discovered that it would have had to wait a year and a half for new ball race roller bearings to be fabricated in Germany. Rather than wait, management decided to fix the discharge boom in place and operate both ladder and discharge booms as a single slewable unit.

As mentioned, the availability of new roller bearings is a problem. In addition, roller frame maintenance is problematic due to tight

clearance and lack of space for men to work.

The conveyor belting employed by BWE's is often a source of problems to both the operating and maintenance personnel. The belts are cut and torn by sharp rocks, wet clay-like material adheres to them, and a general buildup of dirt in the conveyor belting system requires regular cleaning sessions. To ensure a uniform conveyor feed, prolong belt life, and decrease shocks at the transfer point, rollers and rotary disc feeders are installed on some machines. One mine increased its slope sheet life by switching from steel plate to a teflon based slope sheet. This also eliminated some problems caused by material buildup at this critical transfer point.

Some mines experienced problems with the numerous sequential tripper switches situated throughout their BWE's. The switches are designed to prevent excessive loading on structural members and machinery. One mine had problems with the tripper switch located beneath the discharged point of the stacker boom. Every time the operator came within a few feet of the top of the spoil area, the stacker boom tripper switch was activated. This switch activated other switches, resulting in the entire unit being shut down. Then a maintenance man had to spend about 20 minutes resetting the switches in proper order before the BWE could be operated again.

Dust was a problem, particularly at one mine where heavy duty filters had to be installed on the engine blowers and other susceptible areas. These filters had to be cleaned regularly by maintenance men.

Some mines use a beltwagon in conjunction with their BWE in order to achieve the spoil distance they require. This beltwagon could be looked upon as an auxiliary BWE unit which adds to the maintenance burden to be carried by a mine.

CLIMATOLOGICAL

There are four weather related difficulties to be considered at any bucket wheel excavator operation. They may occur singly or in groups. Two of these, excess rainfall and freezing temperatures, occur commonly at U. S. coal mines. Excessive rainfall, especially in the form of sudden storms, may occur at all the mine sites, both successful and otherwise. Rainfall related problems occur at two points in the bucket wheel excavator system. First the material to be excavated, if high in clay content, changes its physical characteristics when well wetted. Usually it becomes increasingly sticky, both more cohesive and adhesive. If sufficient water is added to the loosened clay it may eventually become very slippery with a watery surface layer. Both of these characteristics are difficult to deal with. Buckets may become plugged, belts become

coated with a layer of clay which cannot be removed by ordinary belt cleaning methods, and the watery clay may render the belt drive pulleys less effective. If the belt must be stopped or started, excessive rainfall may have lubricated the belt and its drive pulleys so that its inertia cannot be easily overcome, thus causing excessive belt wear and drive mechanism stress.

Freezing temperatures cause material to freeze to the buckets if any free water is present in the material to be excavated. This results in difficult bucket emptying characteristics and belt sticking problems. Heating units have been used to prevent such problems, but these are energy intensive and generally wasteful. Another problem associated with freezing applies directly to the overburden. In moist overburden, freezing of the upper layers may cause an increase in hardness to some considerable depth. This requires greater power to dig the frozen layers. The frozen material may also have distinctly unfavorable size characteristics which interfere with bucket fill factors. Hard frozen lumps may act in a manner similar to hard rock fragments with all the concurrent problems associated with them once they enter the transport conveyor system. Very low freezing temperatures, such as those encountered in the Northern Great Plains Region, could also require special attention to the hydraulic systems used on almost all bucket wheel

excavators. Even special belting and cables might have to be used in areas where extended periods of low temperatures are encountered.

Two other climatologic factors are of minor importance in U. S. mines. The first, high wind speeds, may cause belt alignment problems in long high speed discharge or ladder conveyors. These alignment problems may result in belt damage from excessive abrasion against skirt boards or loss of material over the belt edges due to deformation of the belt.

The second of the minor problems associated with weather is that of high temperatures. None of the mines visited reported specific problems, but high temperatures could be expected to increase drying of the material being worked and increase the amount of dust generated by any excavating machinery.

MECHANICAL

There are four areas of bucket wheel excavators that are subject to major mechanical difficulties:

1. The Bucket Wheel
2. Mechanical Drive Systems
3. Conveyor Belts & Booms
4. Crawler Assemblies

A detailed analysis of each of these areas will show the causes of mechanical failures.

The Bucket Wheel

The most predominant problems with bucket wheels are tooth and transfer sheet wear, and tooth breakage. Wear on the teeth and transfer sheets is essentially caused by the motion, under pressure, of overburden with respect to the bucket in a direction parallel to the contacting surfaces.

The greater the resistance to this motion (frictional resistance), the greater the likelihood of metal displacement from the bucket surface (wear). Figure 13 illustrates the interrelationship of variables that form frictional resistance.

It becomes immediately obvious from the equation that a decrease in either the coefficient of friction (μ) or the normal force (N) will cause a corresponding decrease in the frictional resistance (F_k) and, thus, a decrease in wear.

In order to decrease the normal force (N), either the weight of material handled (W) must be decreased or the angle (Θ_h) must be increased. Since the weight (W) of the material is a function of geological conditions, manipulation of this term is not considered to be a workable option. By increasing the angle (Θ_h), friction can be effectively decreased because $\cos\Theta$ approaches 0 as Θ approaches 90° . This, however, causes a problem due to the fact that an increase in the angle of incidence will

$$F_k = \mu_k N$$

F_k = Force Due to Kinetic Friction

μ_k = Coefficient of Kinetic Friction

$N = W \cos \Theta$ = Force Normal to the Plane of Motion

W = Weight of Material Handled

Θ = Angle of Elevation from the Horizontal

FRICTIONAL FORCE DIAGRAM

FIGURE 13

cause an increase in the force at the bottom of the bucket or on the conveyor. For this reason, an increase in the angle (Θ_h) is not recommended.

That leaves us with manipulation of the coefficient of friction (μ). This term can be effectively decreased by choosing one of several options. An in-depth discussion of alternatives follows in the section entitled "Recommendations to Improve Mechanical Availability".

Tooth breakage can be caused by excessive impact loading. Figure 14 illustrates the resolution of forces for a tooth when impacting material to be excavated.

RESOLUTION OF FORCES

FIGURE 14

The horizontal force component acts as a compressive force which can cause fatigue failures at points a or b. The vertical component of force can cause the tooth to shear or, if the tooth is loosely mounted, fatigue failures will result at point a or in the retaining pin. In addition, excessive impact loading will cause the tooth to fracture if it can not absorb the total energy generated by the impact.

Mechanical Drive Systems

Mechanical drive systems are especially susceptible to serve

impact loads. This is a result of the mass of overburden excavated being added to the mass of the bucket wheel over a short period of time. The principle of impulse and momentum can be applied to yield,

$$mv + (\Delta m) v_a + \sum F \Delta t = (m + \Delta m)(v + \Delta v)$$

where;

- m = mass of the bucket wheel
- Δm = mass of overburden to be excavated
- v = velocity of the bucket wheel prior to impact
- Δv = change in velocity resulting from the impact
- v_a = velocity of the overburden to be excavated
- $\sum F \Delta t$ = sum of the impulsive forces

Rewriting the equation and solving for the sum of the impulsive forces,

$$\sum F \Delta t = m \Delta v + \Delta m (v - v_a) + (\Delta m)(\Delta v)$$

At this point, relative velocity (u) with respect to the particles absorbed can be introduced. If, $u = v_a - v$ and $v_a = 0$ (overburden is initially at rest) then $u = v$. Dividing through by Δt and letting Δt approach zero, at the limit yields

$$\sum F = \frac{d}{dt} (mv)$$

Conservation of Momentum

This principle, coupled with conservation of energy, can be used to analyze damage to drive systems.

If the bucket wheel attempts to dislodge a large rock, the effective

total mass to be moved is increased due to its resistance to motion. This increases the momentum and energy required to turn the wheel. If the drive system cannot generate the energy required to move the rock, failure of the drive system can result.

Conveyor and Boom

The most serious problem encountered with the conveyor and boom are related to contact with large and/or sharp rocks. As the rock is expelled from the bucket, it contacts the conveyor belt with a great deal of force. The resiliency of the conveyor allows the rock to oscillate. This can be damaging in two ways:

1. The oscillating rock can contact the boom with sufficient force to separate the weld joints.
2. The constant oscillation of the rock on the conveyor belt causes alternate tension and compression stresses. This condition can lead to fatigue failure in the belt.

Damage to the boom and conveyor systems can be extensive depending on the amount of rock encountered by the BWE.

Crawler Assemblies

Most frequently, crawlers break down when operating in wet clay. The pressure of the BWE tends to force the clay in and under the tracks. Further, the clay is not allowed to dissipate due to the adhesion of the

clay with the crawlers. Eventually, the clay builds up to a point where the crawler tracks are forced to separate and failure occurs. Failures of this nature are, of course, most common during periods of excessive rainfall.

Although solutions to the problems mentioned in this section may not be readily apparent, recommendations to minimize their effect are addressed in the section entitled "Recommendations to Improve Mechanical Availability".

RECOMMENDATIONS FOR FUTURE RESEARCH

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RECOMMENDATIONS FOR FUTURE RESEARCH

Bucket wheel excavators have enjoyed only limited success in the United States due to several interrelated factors. This study has identified major areas that contribute significantly to this lack of success.

Although the natural phenomena that present operational and/or mechanical problems to BWE operators can not be removed, their effects can be minimized through extensive research and development efforts.

In the past, obstacles that were encountered by the bucket wheel excavator were circumvented by using other stripping equipment. This has caused BWE underutilization. In addition, if a mechanical failure occurred, a superficial field solution was adopted. These remedies are, very often, only temporary. This leads to chronic failures and trends to increase overall downtime.

By directing research efforts at finding practical solutions to the problems facing BWE operators, certain downtime elements can be permanently eliminated. This section offers recommendation for future research projects that, if undertaken, will act as a catalyst to improve BWE availability.

BWE SELECTION CRITERIA FORMULATION

Prior to adoption of a bucket wheel excavator for use in a sur-

face coal mine in the United States, various aspects of the mine plan must be considered. Due to the great expense of these large excavating units it is absolutely critical to establish guidelines by which a mine operator can determine the applicability of a BWE to a particular operational situation.

Research should be undertaken to establish a simple yet accurate field method for determining overburden characteristics. This is by far the most critical of the variables to be considered. From this determination, cutting resistance factors can be applied and an analysis made of the volume of material compatible with current BWE design.

In order to apply valid cutting resistance factors to a broad range of materials, a standardized testing program must be developed and adopted throughout the entire industry in order to eliminate wide variations within overburden categories. By normalizing these factors, power consumption, tooth design and various other operating parameters can be determined. Material characteristics to be investigated should include the abrasive nature of the material, friability, cohesiveness and fragmentation size once excavated. If these factors exceed certain limits, they can be detrimental to the continued operation of a bucket wheel excavator. These factors, coupled with mechanical-electrical availability as previously outlined in this study, mine sites topography, anticipated production schedule and discounted cash flow requirements

should give the mine operator a realistic estimate of BWE cost per ton of coal. Discounted cash flows can then be used to compare various alternate stripping methods. Once it has been decided that a BWE would contribute significantly to a mine's plan, an equipment matching process should be undertaken to insure optimum equipment utilization and continuous output.

Develop Overburden Test to Determine Potential Problem Areas

Testing of the overburden material for its amenability to a bucket wheel excavator's capability should follow a sequential program. First, before the exploratory drilling phase, drill crews and geologists working together, and keenly aware of the potential limitations of a bucket wheel excavator in handling material, must cooperate to design a drilling program which has the greatest likelihood of discovering any significant layers or lenses of hard rock. If local or regional geologic appraisals indicate the possibility of difficult areas, then these must be sought.

The most important requirement here is to emphasize to the exploratory personnel the necessity for complete information. Drilling patterns must be designed to increase the probability that hard layers or even dispersed boulders above a certain size or frequency of occurrence are discovered. For areas where only doubtful information

about the subsurface is available, a random drill hole method might be used. If a statistically significant sample of holes was drilled then a quantitative estimate of the distribution of the actual population of problem areas could be made. Those drill holes which encountered hard material when displayed on a map would show areas which should be drilled intensively to delineate large lenses.

Coring and subsequent field/laboratory testing of the recovered cores for cutting resistance would make decisions more accurate as to the effect the difficult material would have on future equipment choices. At the two unsuccessful bucket wheel excavator sites unexpected rock was the major cause for their abandonment. In each case, a standard drilling/testing program had failed to reveal the existence of these quite large layers. With fairly unsophisticated statistical sampling techniques these problems of undiscovered rock could be avoided if mine personnel were aware of their necessity.

New methods of recovering shallow subsurface structural information without the time and expense of drilling should be developed. If a graphic display of the three dimensional block of material could be developed, mine planning would be less fraught with guess work. This aspect of research should not be ignored. Subsurface techniques, once developed, could be extended beyond the premine planning stage to

continuous application. At present, the best method is drilling on a close grid with a large enough number of holes to discover areas of difficult digging. This can then be refined by further drilling and simple statistics to circumvent the problem.

CUTTING RESISTANCE FACTOR EVALUATION

Resistance of overburden to cutting by a bucket wheel excavator is determined by the nature of the parent material, its history subsequent to its formation, and to a lesser extent the current climatic regime of the area. All these factors must be considered in any research testing program used to determine the overburden material's suitability for removal by a bucket wheel excavator. Cutting resistance is simply the resistance of the overburden material to being cut or dug out of its position. The resistance depends upon the hardness of the material and the fabric of the layers in which it occurs. A moderately hard sandstone may be dug using a modified bucket wheel if it is consistent; however, an isolated boulder of this same sandstone encountered while buried in a soft matrix may fracture instead, or merely become dislodged intact. Cutting resistance is usually evaluated in one of two ways:

- a. the resistance to digging in relation to cross sectional area of the slice taken by the bucket - kilograms of force/

square centimeter of area (common in non-German literature) or

b. the relation to the length of the effective cutting edge – kilogram of force/centimeter of cutting length (common in German literature).

There are several published cutting resistance lists as a result of tests performed on various materials found in surface mining (see Figure 15). These figures, however, must be used with caution since the materials cut are only broadly defined. Each test is site specific because of the complexity of the interacting factors that have produced a given texture to any soil or overburden material.

Field techniques should be oriented towards identifying each major component of the overburden to be removed. The entire area under consideration must be examined in enough detail to discover the distribution of layers or isolated occurrences of any layers that differ significantly in resistance to cutting from the bulk of the overburden. Boulders embedded in clay or soil layers must be accounted for and their size, distribution, numbers, and hardness known. The geologic history and local structure of a mine property may give an indication of their presence. For example, in an area known to be covered by glacial, periglacial, or fluvial sediments there exists

**SPECIFIC CUTTING FORCES OF
UNEXCAVATED MATERIAL**

FIGURE 15

the distinct possibility of buried layers of resistant material transported in these high energy environments of deposition.

Field testing for cutting resistance values has not been a major factor in the premine planning at any mine in the United States. However, Mine H personnel reported that a consulting firm had made tests during their initial study prior to adopting a bucket wheel excavator, and Mine I reported that their machine manufacturer had conducted tests on material from the site. No information was available as to the type or nature of the tests performed. In general, cutting resistance tests were not a consideration in determining current mine planning except in one locality.

Mine F in Illinois used a homemade triaxial vane stress machine and a torque wrench to conduct tests on material they planned to excavate. Since cutting resistance is such a variable characteristic, field testing would be labor intensive, and therefore costly if done completely. The block of overburden to be removed would have to be studied over its entire area and throughout its depth from closely collected samples. If a comprehensive exploratory core drilling program were conducted, material that yielded high cutting resistance values could be tested using triaxial compression/stress tests in the laboratory, however, field methods are generally limited to the surface or near surface of undisturbed overburden or highwall faces.

Tests should be devised or parameters established that would allow the operators of exploratory drilling equipment to identify and locate hard layers not exposed at the surface. Resistance to drilling as recorded by the operators could give an initial indication of potential trouble spots. These areas could then be cored in detail with samples of the hard layers collected for intensive laboratory analysis. This second stage of core drilling could also delineate the areas of harder rock for evaluation of detrimental effects on the entire mine scheme.

Laboratory tests on samples must be considered in relation to the entire area under consideration. For example, if the area to be mined is large and the relative area of resistant material is small, perhaps only a slight change in equipment would solve the problem. Conversely, if the area were large and the overall hardness marginal, an alteration of the extraction plan or type of cut might yield an economical mine. Laboratory testing of cutting resistance of samples may be full scale simulations of bucket teeth pulled through a large block of overburden with measurement of the force applied.

In other methods a single tooth is applied to a block of rock or soil and the force required to make an impression in the material is measured. In more elaborate tests compression forces can be measured. It must be understood that these tests begin to deviate radically

from actual digging conditions encountered in the field. At present, cutting resistance is not often determined by either field or laboratory methods by U.S. coal mines. It is possible to derive cutting resistances from an adaption of the following formula:

$$K = N_G \times \eta \times C \div (Q_a \times S \times R)^{\frac{1}{2}}$$

where:

K = specific cutting resistance in kg/cm.

S = no. of bucket discharges/min.

Q_a = actual capacity in m³/hr.

R = radius of bucket wheel in m.

N_G = digging power rating of the drive in kw

η = efficiency of the motor drive

C = constant depending upon the bench height to wheel diameter ratio. C increases with decreasing bench height for a given wheel diameter.

(Price, et. al., 1973)

These cutting resistance values are useless for premine planning since they presuppose an active bucket wheel excavator. They could be useful in mine planning to enlarge its bucket wheel excavator application if they were carefully kept over a period of time. If the actual conditions at the proposed new site were radically different than calculated, extensive testing would be necessary. However, if calculated cutting resistance values were similar to actual conditions, a correlation could be made. At present, no uniformly applicable field or laboratory tests are available to evaluate cutting resistance before a bucket wheel excavator is installed at a mine. For such tests to become an important part of premine planning, they should be designed as an

integral part of the exploratory program. This will enable the mine management to make early equipment match decisions.

Research should be devoted to enabling a geologist, working in conjunction with a drill crew, to judge cutting resistance from drill behavior and core samples. A research program could be developed through which certain physical features of a rock or soil sample, obtained from a drill core could be compared to materials of known cutting resistance. Physical characteristics such as hardness, grain size, grain shape, and degree of particle consolidation in sedimentary rocks could be useful field indicators of cutting resistance. A series of cutting resistance tests based on a standard method of laboratory analysis, such as the forces necessary to split a block of known composition with a bucket wheel excavator tooth of standard geometry, could be prepared.

Other factors involved in cutting resistance, i.e. tooth angle of attack, number of teeth, or sharpness of teeth would then be amenable to testing once the standards were established. All the tests should be conducted on soil or rock samples collected from actual mine sites and should cover the entire range of materials encountered. Also, the number of samples of each type must be large enough to be statistically significant. Ultimately, tables giving the significant variables of rock composition and their cutting resistance range would be available for geologists

and engineers to apply to specific site testing.

RECOMMENDATIONS TO ELIMINATE EQUIPMENT MISMATCHES

The major attribute of a bucket wheel excavator is its ability to continuously excavate large volumes of overburden. Superficially, this would appear to be a great asset to any mine that uses a BWE. Unfortunately, however, this is not always the case. In United States' coal mines, the BWE is used to excavate the easy to dig glacial till. This usually consists of about 20 feet of material. The remaining overburden, normally about 80 feet, must be handled by an alternate stripping machine. This is because the consolidated nature of the material makes it impossible to be handled by a BWE. Acknowledging this fact, a prime equipment mismatch element surfaces. The mine operator must exercise extreme care in selecting a BWE in order to minimize operational delays.

In the United States, stripping shovels are used in conjunction with the BWE's. The productive capacity of a shovel can be defined in much the same manner as previously derived for the BWE:

$$P = (B_C \times f_B) \times t_C \times A_M$$

Where,

P = Productivity (cubic yards per hour)

B_C = Theoretical bucket capacity (cubic yards)

f_B = Bucket fill factor
 t_c = Cycle time (cycles/hour)
 A_M = Machine availability

This productive capacity must be closely matched to that of the BWE in order to optimize production and minimize operational delays.

Suppose, for example, that a company owns a BWE that has a productivity of 1500 cubic yards per hour. A decision is being made on the size and type of auxillary stripping equipment needed to work with the BWE. If the auxillary stripping unit must excavate 80 feet of material to 20 feet excavated by the BWE, the productive capacity of the auxillary unit must be 4 times as great as the BWE or 6000 cubic yards per hour. If a shovel is being considered that is capable of 72 cycles per hour and an assumed availability and bucket fill factor of 90% and 98% respectively, the shovel must have a bucket size of:

$$B_C = \frac{6000}{(.98)(72)(.95)}$$

$$B_C = 89.5 \text{ cubic yards}$$

In this case, as in most cases, the theoretical bucket size falls between manufacturers specifications. At first glance, the decision may be made to purchase the next larger size shovel. Such a decision could be very costly. Although the capacities of the two machines would be matched, the cost to purchase, operate and maintain the

larger unit may be far in excess of the costs for a smaller machine.

To determine least net cost, several factors come to bear:

- P = initial equipment cost
- n_1 = number of years of useful equipment life
- n_2 = number of years for cost comparison
- L = salvage value of the equipment
- i = specified interest rate
- c = annual operating expenses including depreciation, downtime and operational delays
- $(v_i)^n$ = single payment present worth factor @ i rate of interest for n years
- $P_{n,i}$ = annuity present worth factor for @ i rate of interest for n years

Total cost (T) is described by the following relationship between these terms:

$$T = P + (P - L)(v_i)^{n_1} + C (P_{n_2,i}) - L (v_i)^{n_2}$$

Costs should be calculated for each machine and compared to obtain realistic parameters for equipment selection. A decision should be made based on this comparison.

A similar productivity/cost analysis should be made to justify the use of a dragline in combination with the BWE. The concept as previously presented in Figure 3, page 15 of this report shows such an arrangement. The advantages of using a dragline over a shovel are:

1. Longer casting distance of the dragline with respect to the shovel.
2. The dragline is commonly available with a larger bucket size than the shovel.

3. The dragline does not operate in the pit, thus, reducing the pit width required.

One pitfall associated with equipment purchases is to assume that bigger is better. It can be seen from the preceding analysis that this is not always the case. This is not to suggest that a larger capacity machine can be outproduced by a smaller machine under similar circumstances. It does, however, suggest that the interrelationship of productive capacities, economics and operational downtime determine the optimal size of equipment to be purchased.

RECOMMENDATIONS TO IMPROVE BLASTING TECHNOLOGY

All mines in the U.S. currently using BWE's for overburden removal do not blast the overburden. This is because BWE's have been implemented only where the overburden consists of glacial till or loosely consolidated sediments.

With blasting, a BWE could be used to excavate consistent layers of sandstone, shales, and limestones. A closer drill pattern and a higher powder factor would have to be used than if the rock were being blasted for excavation by a dragline or shovel. This is due to the limited size of the individual digging buckets of a BWE. The rock would have to be overshot somewhat in order to reduce it to a size which could easily pass through a BWE's smaller bucket opening. This overshooting would

result in higher than average blasting costs and would cause increased problems in the areas of flyrock and dust control. Tooth wear would also increase due to the generally more abrasive nature of fragmented rock as compared to loosely consolidated material.

As mentioned previously, it is very important that the rock layer be consistent in nature, so that when blasted, the resulting fragmented material is also of consistent size with no larger boulders resulting. An overburden layer consisting of alternating solid rock and unconsolidated material containing isolated boulders will cause a blasting program to fail. Isolated boulders too large to pass through an individual bucket and surrounded by relatively soft unconsolidated material would be unaffected by blasting. The blast would not fracture the rock and in all likelihood it would just shift its position within the unconsolidated layer. Large isolated boulders can damage the bucket wheel and require auxiliary equipment in order to remove them from the overburden. A study is currently under way by Skelly and Loy to detect isolated boulders and destroy them in place. The success of this project could prove valuable to mines operating BWE's.

A mine operator, when deciding whether or not to use a BWE in overburden requiring drilling and blasting, must consider the additional costs of drilling, blasting, deadtime associated with blasting,

and increased tooth wear. In addition, an operator must be sure of the consistency of the overburden in question and, of particular importance, whether or not frequent isolated boulders imbedded in unconsolidated layers do exist.

Future research is needed in two major areas. First, new economically feasible drilling and blasting practices must be developed to insure that a consistent size results from a shot. Second, economical methods must be devised to determine the nature and consistency of the overburden to be excavated. These overburden testing methods should delineate and identify layers of rock and unconsolidated material as well as detect the presence and frequency of isolated large boulders.

RECOMMENDATIONS TO IMPROVE MECHANICAL AVAILABILITY

To date, the utilization of BWE's in the United States has been concentrated at several large scale mines in the Illinois Basin. At the time the BWE was introduced, these were the only mines operating that had conditions suitable to support the large scale investment represented by the BWE. That is, the mine sites are characterized by relatively flat topography and the overburden contains a sufficient quantity of friable material to accommodate the use of BWE's. In the years that followed, however, improvements in both large and small

scale BWE's and increased interest in nationwide coal resource development led to feasibility analyses of applying BWE's to coal recovery problems in areas outside their traditional stronghold. In addition, overburden segregation as dictated by Federal regulations has forced operators to explore new methods of cost-effectively handling large volumes of material while controlling its placement for the purpose of reclamation.

In order for the BWE to become an effective tool for surface coal miners in the United States, variations must be made in machine design to facilitate its use under various geologic and topographic conditions. Research efforts could be funneled into various design and development projects that could act as a means to this end.

Excessive forces and impacts should be a major consideration in the design of mechanical components. Figure 13 on page 122 of this report shows a breakdown of frictional forces. As previously mentioned, the only viable option to reduce frictional forces is to decrease the coefficient of kinetic friction. In order to realize a significant decrease in this term one of several recommendations should be implemented: (1) coat the bucket wear surfaces with a friction resistant plastic material (i.e. teflon, ultramid, linerite, etc.); (2) spray or bake silicon onto the surface, or; (3) impregnate the metal with graphite (this process is being used successfully in other industries to decrease wear of like materials). Worn cutting surfaces that result from friction are

considerably less efficient and cause a direct increase in power consumption per unit of material excavated.

WEDGE TYPE INTERFERENCE FIT TOOTH

FIGURE 16

Tooth breakage due to excessive impact loading and fatigue caused by loosely fitting bucket teeth is also a problem. To remedy this condition, the use of high strength, high nickel content alloys should be investigated. Further, a wedge type, interference fit tooth to shank arrangement as illustrated in Figure 16 should be considered to eliminate loosely fitting teeth.

A resilient pad could be inserted at the bottom of the tooth opening and a tapered retaining pin used to minimize the effect of locating hole mismatch. Since the shank is wedge shaped, a close fit can be maintained between the tooth and the shank. This will allow the tooth and shank to act as a single unit, thus decreasing the possibility of fatigue failures.

Another problem experienced by most BWE operators, is the discharge of large rocks that tend to oscillate due to the resiliency of the conveyor belting. This can cause damage to the belting as well as the structural members.

Figure 17 illustrates a proposed solution to this problem.

OSCILLATION DAMPING SHROUD (Cross Section)

FIGURE 17

By incorporating a sloped shroud over the conveyor at the bucket discharge point, oscillating material will reach equilibrium before any damage can occur.

Other problems included crawler separation due to wet pit conditions. To counteract this phenomenon, the use of blades to strip material from the face of the crawlers should be investigated. In addition, the use of plastic coatings and lubricating materials, as previously mentioned in the bucket wheel section, is also recommended in order to decrease the amount of adhesion between the clay and the crawlers. Further, a study should be conducted to determine the feasibility of using walkers to replace the crawler units.

The field studies indicated that, due to the BWE's large capacity relative to the primary stripping unit and the lack of sufficient amounts of glacial till to be excavated, the BWE sits idle for long periods of time. Evidence of this condition can be found in Figure 7 on Page 72 and Figure 8 on Page 74 of this report. Research to improve this situation should be directed toward the development of smaller more mobile BWE's to both increase economic feasibility and keep production in line with the other stripping equipment. Another option would be to examine the possibility of developing a multi-wheel excavator. Figure 18 shows a concept for a multi-wheeled machine. The lower wheel is designed to excavate unshot rock while the upper wheel is used

to remove the easy to dig glacial till. This design has many advantages over conventional, single wheeled excavators. For example: The addition of a second wheel would allow the BWE to excavate twice as much material in the same period of time. With more of the highwalls excavated, the stripping shovel would be capable of keeping pace with the BWE. In addition, the use of dual conveyors would serve as an excellent means of material segregation.

In order to achieve the goal of excavating rock with a BWE, a minimum shear wheel must be developed. Figure 19 depicts such a wheel. It can be seen from the illustration that the wheel would reduce the forces required to excavate rock. The outside rails make the initial cut much the same as a circular saw. The excavating blades are recessed and only remove material after the initial cut has been made. This reduces the effective force required to shear the surface.

As a prerequisite to any new mechanical design an intensive investigation into new materials should be undertaken. Inconel, Hastalloy, and highly tempered (T-6) aluminum alloys are among the materials that should be considered. Due to the high nickel content in Hastalloy and Inconel, these alloys offer high strength, good impact resistance and minimum sensitivity to extreme heat. For extreme wear conditions, overlays of cobalt base alloys should be investigated. Aluminum, although impractical for use in the cutting wheel, should be

considered in the design of the superstructure. This would greatly reduce weight which could increase boom lengths and decrease power consumption.

Ancillary to new materials is the investigation into friction resistant coatings. As previously mentioned, research into graphite impregnation as well as coatings on the cutting surfaces such as silicon, teflon, linerite, etc., could greatly increase BWE productivity.

If the bucket wheel excavator is viewed as a single unit, redesign becomes an extremely difficult task. However, if the BWE is viewed as a system of small, interdependent mechanisms, improvements can be made to each mechanism that will affect the productivity of the entire system.

One example of this is controlled spoil discharge. By varying the speed of the discharge conveyor, spoil can be cast to various distances. This minimizes peak height on the spoil piles and aides reclamation. It should be noted, however, that this is limited by belt widths which are sized for lowest speeds. Another possibility is the use of multiple discharge conveyor systems utilizing different lengths. By using different conveyor lengths, spoil can be funneled onto each conveyor and cast to predetermined sites. A shuttle conveyor system similar to those used in stockpiling iron ore should also be investigated for spoil placement. Other examples are improvements in belt alignment, use of coatings on conveyor belts to eliminate sticking, tooth

design for hard shales, materials to protect cables, shocks on idlers in heavy loading zones, pre-cut ply separation in conveyor belting for ease of replacement, use of room temperature vulcanizing compounds to repair belting, and elimination of conveyor idlers. The list of possible improvements is endless.

Aside from the above-mentioned equipment research, a series of mine plan models should be developed to minimize some of the operational delays such as deadheading and no spoil room. These plans should include specific information concerning geologic and topographic conditions as well as pit development criteria to determine BWE suitability.

In addition, research for development of equipment to measure cutting resistance should be undertaken. Such equipment could be used in pre-mine planning as an aid in determining the most effective and efficient equipment utilization.

Although the BWE is used on a large scale in Germany, increased utilization of these machines in the United States is dependent upon continuing research and development. Increased productivity will result only through the interrelationship of advanced equipment designs and effective mine planning.

CONCLUSIONS

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CONCLUSIONS

In recent years, coal production has been stepped up to help satisfy the Nation's increasing demand for energy. This increase in coal production generated a need to develop improved extraction technology. The Bucket Wheel Excavator is one such improvement.

The concept of a BWE offers continuous excavation capabilities along with controlled spoil placement and mobility. These machines combine all vital mining operations into one synchronized unit. As a result, overall efficiency should be at a peak and costs controlled to a minimum when the BWE is operating at full capacity.

The problems related to the introduction of a new machine into the market place are directly related to its size and complexity. Therefore, when the bucket wheel excavator was introduced to the environment of United States coal mining, applications problems developed as expected.

Due to their complexity and the interrelationship of components, the magnitude of the problems were expensive and time consuming to cure. Although there are still various problems that limit their availability, efforts to increase the adaptability of BWE's to United States surface coal mining should not be abandoned.

If the bucket wheel excavator is going to assume its place in the

American coal mining industry, casual relationships must be determined on a site specific basis in a manner that is both timely and accurate.

It is certain that each mine has geologic, topographic and climatologic conditions unique to that operation. Therefore, a BWE should be matched to each set of conditions. This is not to say that a completely new design is needed for each mine, rather, each machine should be fine tuned to handle the adverse conditions of a specific site. If, for example, a site contains large amounts of rock dispersed throughout the overburden, different digging heads and suspension systems should be available to handle the situation.

As they are presently designed, BWE's are unsuitable for use in areas when there is a high incidence of rock. This situation severely limits their use in United States surface coal mines. However, if the recommendations presented in this report are implemented, along with an on site analysis of potential problem areas, the applicability of BWE's can be expanded to a point when they can become a cost effective means of overburden removal.

With the support of government funded research projects, productive capacities can be increased and overall mining costs reduced. This could result in an overall decrease in the cost of energy. Although larger European machines could increase capacities in areas where there are only slight occurrences of rock, they would be cumbersome

and costly if large amounts of rock were encountered. According to the information received during the course of this study, the technology to excavate a wide range of strata has not yet been developed. Once the technology is developed to excavate a wide variety of materials, larger BWE's can then be utilized to effectively increase productivity. Funding of these recommended research projects may bring the United States one step closer to its goal of energy self-sufficiency.

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