EVALUATION OF MECHANICAL EXCAVATION SYSTEMS FOR OIL SHALE MINING

Final Technical Report

By
Levent Ozdemir
Russell J. Miller
William R. Sharp

July 1983

Work Performed Under Contract No. AC20-82LC10962

Colorado School of Mines
Golden, Colorado

TECHNICAL INFORMATION CENTER
U. S. DEPARTMENT OF ENERGY
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ABSTRACT

This report presents the result of an investigation into evaluating the technical and economic feasibility of applying mechanical excavation techniques to oil shale mining. The study was funded by the Department of Energy, Laramie Technology Center. Based on the findings of this investigation, it was concluded that mechanical excavation systems offer a great potential for oil shale mining in terms of high production and reduced costs compared to conventional methods. While some of the systems evaluated can be applied to oil shale economically in their present stage of development, others require additional improvements to ensure maximum benefit and applicability for various aspects of oil shale mining operations. It is also suggested that current mine design approaches may need to be modified to gain maximum advantage from potential utilization of mechanical excavation techniques.
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I. INTRODUCTION

The needs for new energy sources and oil shale's potential role in satisfying our nation's energy requirements are well documented. The concern here is how to best facilitate the removal and processing of the vast amounts of oil shale required for the envisioned industry.

The production rate often implied for a mature shale oil industry is one million barrels of synthetic crude oil per day (BPD). This level of production would require mining over one and a half million tons of oil shale per day. To be able to take advantage of economies of scale, it is estimated that individual projects will have to operate at a minimum capacity of 50,000 BPD, with many having much higher levels of production. It is evident that even the "small" oil shale operations will be faced with the removal and handling of massive amounts of material, both before and after processing. True in situ approaches would mitigate this problem, but that method has not been successful to date. The more feasible modified in situ approach still requires the excavation and removal of very large tonnages of material for development and the generation of void volume.

For surface retorting operations, it is considered feasible to provide the required retort feed from an underground room and pillar mining operation, although for a 50,000-BPD plant, the mine would be larger than any current underground mine. Obviously, requirements for development, production headings, equipment, skilled labor, and material handling would be formidable. Even open-pit mining faces requirements of similar magnitude, although more experience exists in large-scale pit operations.

Under the constraints of current mining approaches and prejudices, the costs of producing shale oil have kept ahead of world oil prices. It would appear that it is time to consider new mining approaches or improvements
to existing methods that would better suit the scale of operations and the particular characteristics of oil shale. With that in mind, the purpose of this report is to evaluate the applicability of mechanical excavation to oil shale; identify available machine types that are best suited to various aspects of the mining operation; provide production and cost estimates to allow a benefit analysis; present preliminary comments on the configuration of an "ideal" oil shale mining machine; and establish the background information necessary for conceptualizing and evaluating new mining techniques using mechanical excavation equipment.

There are two separate aspects of a mining operation to which mechanical excavation equipment would be applicable: development and production. Since the needs of each can be quite different, it is important to consider them separately in evaluating the suitability of mechanical excavation.

For underground mining, the evidence suggests that development headings using full-face boring machines could actually progress faster than conventional drill and blast, apparently at lower cost. This is not the only advantage; factors such as a more stable opening, uniform muck size, ease of muck handling, better ventilation, less equipment, increased safety, and a reduced manpower requirement would seem to make development by machine very attractive. As full-face machines are not as flexible, it would be advantageous to use development drives as long as possible in order to use the machines most effectively. Partial-face machines can also be considered for development. While their advance rate is considered to be less, the other advantages are similar to the full-face machines, and are definitely significant.

In a production mode, it is admittedly difficult to compete with large-scale blasting in terms of costs for breaking rock. If, however, the side benefits of mechanical excavation are taken into account, there is an excellent chance that overall costs will be reduced.
example, an underground room and pillar mine, several advantages can be identified: (1) reduced damage to roof and pillars, which will permit a significantly higher extraction ratio, improved safety, and better ventilation; (2) controlled, uniformly sized muck, minimizing or eliminating crushing, improving material handling, and providing an optimum feedstock for certain retorts; (3) ideally suited for integration with a continuous material handling system such as belts, a factor which has its own advantages in being continuous, clean, and not requiring large numbers of trucks and attendant maintenance, safety, and ventilation considerations; (4) continuous in nature, not requiring delays for blasting, mucking, sealing, and fumes removal; also eliminates the variety of equipment associated with cyclic drill and blast, reduces or eliminates the need for surge points in the system, and allows smoother production planning; and (5) can be easily adapted to selective mining where zones of desired grade can be mined sequentially or low-grade material can be diverted for in-mine disposal.

Several of the advantages of mechanical excavation for an underground mine should also be applicable to a surface operation. Obviously, continuous operation, uniform muck size, belt haulage, and the ability to selectively mine are attractive alternatives for potential surface oil shale mines. Currently, it is believed that there are no machines capable of competing with available large-scale pit mining concepts. However, data concerning rock-cutting tools and preliminary conceptualizations strongly indicate that machines could be designed and constructed to greatly increase the efficiency of an open-pit operation. In particular, the ability to improve average grade through selective mining has been shown to dramatically improve potential returns, even to the point where increased mining costs could be tolerated to effect such improved average grade. A similar conclusion seems valid for underground mining as well.
This report presents the results of an investigation designed to evaluate the technical and economic feasibility of applying mechanical excavation methods to oil shale mining. The study was divided into three major phases: (1) a detailed literature review of current mechanical excavation systems was undertaken to identify current equipment for potential application to mining of oil shale, both for development and production work; (2) a series of laboratory linear and rotary cutting tests were performed to provide a data base for evaluation of the cuttability of oil shale by various cutting tools and techniques; and (3) an economic analysis was undertaken to determine the cost savings that can be realized by utilizing mechanical excavation techniques in preference of conventional drill and blast methods. The findings of all three phases of investigation are presented and discussed in this report. Also included in the Appendices are the minutes of a conference on "Mechanical Excavation of Oil Shale" which was held at the Colorado School of Mines on May 25, 1982.
II. EVALUATION OF MECHANICAL EXCAVATION SYSTEMS FOR OIL SHALE MINING

As part of this effort, both presently available and potential mechanical excavation systems were evaluated for their potential for mining oil shale. Capabilities, requirements, production rates, applications, and cost were assessed for each machine type. Following is a discussion of the various mechanical excavation systems which were evaluated.

Continuous Miners

Both the ripper- and drum-type continuous miners utilize drag-type cutter bits to break the rock. Depending on the rock type and particular application, the cutter bits are either plow-type or conical (point-attack). The conical bits are generally preferred for cutting harder materials and can withstand larger shock loads. When used on continuous miners, the conical bits rotate in their holder blocks and become self-sharpening. Both types of bits are fitted with carbide tips brazed into the bit body.

Continuous miners are high-production machines with relatively low capital costs. Because of the crawler mountings, they are quite mobile and can drive 90-degree crosscuts and negotiate sharp turns. There is easy access to the cutting drum and to the face being cut. Bits can be inspected and changed with minimal effort. Roof supports, if needed, can be installed immediately behind the machine.

The major disadvantage of the continuous miner is the limitation on the amount of force that can be supplied to the cutting drum. The machines are not braced against the roof or the side walls and therefore the machine's weight provides the sole reaction force for the cutting operation. Because of this, their application is limited to mining relatively soft rock. However, heavier and more powerful machines have been built in recent years for cutting harder material such as iron ore. Several manufacturers have ongoing design and development programs that will produce continuous miners for application
to harder rock.

**Boring Type Continuous Miners**

The boring-miners utilize twin rotors, each with three cutting arms, a drum cutter, and a cutter trim chain for cutting an ovaloid opening. The cutting action is similar to trepanning and produces larger cuttings than other continuous miners. The cutting is accomplished with drag-bit cutter bits mounted on the rotors, the drum, and the trim chain. The machine is crawler-mounted, providing the reaction force for the cutting action. The cuttings are collected and transported behind the machine with a chain conveyor. The largest machines built to date cut a face area 4 meters high and 6 meters wide with an installed power of 15 HP. These machines, which are used in mining potash, weigh as much as 205 tons.

**Boom Type Continuous Miner**

The steadily increasing application of roadheaders to the mining field is due to the several advantages they offer over standard drum-type and boring-type continuous miner. The roadheaders can cut harder material than the continuous miners because the machine power is concentrated over a smaller number of bits. They produce less dust and can negotiate steep grades and tight crosscuts. The machine operation is quite flexible and permits cutting any size and shape cross-section (circular, horseshoe, arched, rectangular). The cutter boom is easily accessible and therefore can be inspected and replaced with minimal effort. Because of the smooth cutting action, the integrity of the roof strata is not disturbed, resulting in savings in roof-support requirements. Furthermore, if needed, roof supports can be installed at the face.

The major shortcoming of roadheaders relates to the production rate they can achieve. These machines are part-face excavators; that is, only a portion of the full-face can be cut at a given time. Therefore, they cannot match the production capacities of full-face machines, such as TBMs or boring-type continuous miners. In recent years, however, major improvements have been
made to increase the production capacity of roadheaders. High production rates have been attained with new, heavier machines with large cutterheads or machines with multiple cutting booms.

**Undercutting Boring Machine**

Unlike TBM's, which attack the rock face frontally and cause rock breakage through a combination of compressive-shear-tensile failure, the Mini and Midi Fullfacers undercut the rock by creating a groove about 20 centimeters behind the face and breaking the rock out to the face. The rotating cutterhead is mounted on a horizontal axis at right angles to the tunnel axis. At the start of a new cutting cycle, the cutterhead is in a downward tuck position. As the cycle proceeds, the cutterhead is swung upward at an angle of 155 degrees from its downward position. The cutterhead rotates at about two RPMs and undercuts the rock using 8 to 14 peripherally fitted drag-bit cutter tools. After it has moved to its maximum "up" position, the cutterhead starts to return to initial downward position, still rotating and directing muck into the flight-chain conveyor at tunnel invert. The downward movement requires about two minutes. No cutting occurs during downward movement. After the cutterhead returns to its start position, the machine is advanced forward and the cutterhead resumes its upward swing action, taking another undercut approximately 20 centimeters behind the face. During the cut cycle, which usually lasts about three to ten minutes depending on rock hardness, the contractor has time to haul muck and move back behind the machine.

**Slot Machine**

Basically, the Slot Machine works on the same principle as a tunnel-boring machine (TBM) with the main difference being the positioning of the cutterhead. Unlike a TBM, where the cutterhead rotates about a horizontal axis, the cutterhead of the Slot Machine rotates on a vertical axis. This results in a rectangular rather than a circular bore and is used in cutting a mine floor.
**Haspert Mining Machine**

The Haspert machine is designed to drive a rectangular heading in oil shale. The machine works on a sloped heading of about 30 to 40 degrees. Under the DOE grant, a preliminary design for a prototype machine is to be developed that can mine a heading approximately 7 meters wide and 6 meters high. The machine used a series of scalpers and kerf-core discs that are designed to break oil shale in a two-step action. The oscillating up and down movement of these tools contributes to the two-step cutting action. In step one, which corresponds to the downward movement of the cutter tool, the scalper assemblies cut relief grooves on the sloped heading while the kerf-core discs cut every other groove. The purpose of relief grooves created by scalpers is to permit core rupture between disc grooves. During the upward stroke (step two), the discs are allowed to roll and rupture the shale cores left between grooves.

**Alkirk Shale Miner**

The operating principle of the machine is analogous in some aspects to a wood bit augering a hole through a block of wood. As the machine advances into the rock, the cutting edges shave off a thickness of rock equal to the advance of the machine. Muck is then transported from the face with helical-shaped flutes.

**Tunnel Boring Machines**

All TBMs cut rock with the same principle. A large rotating wheel fitted with roller cutters is used to cut or spall the rock. The wheel (cutterhead) is slightly smaller than the bore of the tunnel and is equipped with gage cutters to produce the designed bore. The cutterhead is rotated at speeds that may vary from four to ten RPMs depending on the size of the bore. The machine grips itself in the tunnel using a set of anchor pads reacting against the tunnel walls. Cutterhead thrust is provided by hydraulic cylinders. A series of electric motors with pinions driving a large bull gear provide
the required torque for rotating and cutting.

Mobile Miner

The mobile miner is a new machine concept that is currently under development by the Robbins Company, the world's largest manufacturer of tunnel-boring machines. Because of its proprietary nature, very little information is available about the design and operation of this machine. Through discussions with the Robbins Company, enough has been learned to allow an analysis of its applicability to mining oil shale. The machine uses disc cutters mounted on a rotating movable head. It can be considered a partial-face machine, combining the mobility, flexibility, and light weight of continuous miners and roadheaders, and providing the hard rock capability and long cutter life of disc cutters.

Rectangular Boring Machine

A new concept in mine drifting machinery is presently in the research and development (R&D) stage in Harrison-Western's engineering department. The R&D group of Harrison-Western, under the direction of Larry Snyder, is developing a machine to excavate rectangular mine entries and haulage ways in hard rock. Combining existing technology with innovative machine design has led to this new concept in mining machinery.

The concept is similar to the slot machine discussed earlier where a typical TBM cutterhead has been turned on its side and rotates about a nearly vertical axis. By using cutters on the top of the cutterhead a blind entry can be excavated with a nearly rectangular shape. This approach provides the high productivity of a full-face machine while creating a more desirable rectangular entry for oil shale mining.

Based on the above presented literature review of mechanical excavation systems for oil shale mining application, the following conclusions were drawn:
(1) The envisioned oil shale industry will require the removal and handling of massive amounts of material, even for "small" mines.

(2) To make shale oil production competitive, it would appear that it is time to consider new mining approaches or improvements to existing methods that would better suit the scale of operation required for, and the particular characteristics of, oil shale.

(3) Mechanical excavation techniques offer significant potential benefit to the oil shale industry, and should be evaluated for optimal selection of appropriate technologies.

(4) There are two separate aspects of a mining operation to which mechanical excavation would be applicable: development and production. The two applications need to be considered separately when evaluating the suitability of mechanical excavation.

(5) For development headings, mechanical excavation offers the potential for lower costs and higher advance rates. In addition, factors such as a more stable opening, uniform muck size, ease of muck handling, better ventilation, increased safety, and reduced manpower and equipment requirements should make development by machine very attractive.

(6) Although admittedly it does not compete well with drill and blast, mechanical excavation in production for an underground mine offers current, and particularly future, significant benefits. Some of these advantages include: (a) reduced damage to roof and pillars, which will permit a significantly higher extraction ratio, improved safety, and better ventilation; (b) uniform, controlled muck size, minimizing or elimination crushing, improving material handling, and providing an optimum feedstock for certain retorts; (c) ideally suited for integration with a continuous material handling system such as belts, which has its own advantages in being continuous, clean, and not requiring large numbers of trucks and attendant maintenance, safety, and ventilation requirements; (d) continuous in nature, and not
requiring delays for blasting, mucking, scaling, and fumes removal; also
eliminates the variety of equipment associated with cyclic drill and blast,
reduces or eliminates the need for surge points in the system, and allows
smoother production planning; and (e) can be easily adapted to selective
mining, where zones of desired grade can be mined sequentially, or low-grade
material can be diverted for in-mine disposal.

(7) Many of the advantages of mechanical excavation for an underground mine
should also be applicable to a surface operation. Continuous operation,
uniform muck size, belt haulage, and the ability to selectively mine should
be attractive alternatives for surface oil shale mines. In particular, the
ability to improve average grade through selective mining has been shown to
dramatically improve potential returns, even to the point where increased
mining costs could be tolerated to effect such improved average grade.

(8) Extensive theoretical and experimental investigations, both here and
abroad, provide an excellent base for evaluating the potential performance
of individual machines, and for determining actual capabilities rather than
relying on some times overly optimistic manufacturers' claims.

(9) Rock cutting tools come in a wide variety of sizes, shapes, and styles.
These cutters, however, can be grouped into two major categories: Drag-bit
cutters, using a milling or ripping action; and roller cutters, using a
crushing and chipping action. Drag-bit cutters are usually used in softer
formations, whereas roller cutters are best suited to harder, more brittle
rock types.

(10) Oil shale tends to span the range between properties best suited for
drag-bit cutting, up to strengths and hardnesses that generally dictate a
roller-cutter approach. With rock properties in this crossover range, it
becomes critical to evaluate the relative characteristics of the various
cutter types in making a decision as to the most appropriate mechanical
excavation system for oil shale.
(11) Drag-bit cutter forces increase nearly linearly with penetration. Efficiency, or energy per unit volume of rock, improves with depth until a critical depth is reached. For each pick type and rock there is an optimum depth of cut per pass.

(12) Pick cutter spacings and lacing pattern dramatically affect machine cutting efficiency. Knowing the pick type and rock properties, it is possible to identify proper pick placement for optimum performance.

(13) Pick rake angles can be selected for use in oil shale so as to balance pick loads, increase efficiency, and minimize wear.

(14) Cutting speed seems to have only a limited effect on pick performance, but can adversely affect pick life because of heat dissipation problems at higher speeds.

(15) For planer-type bits, in which a wedge of a given width makes up the cutting edge, the width and shape of that edge control cutter forces and efficiency. Using this type of bit and its configuration depends on the type of rock to be cut. Actual trials are about the only way to evaluate the efficiency of these bits.

(16) For drag-bit cutting, cutter wear develops more rapidly and greatly influences overall efficiency. Even small amounts of wear can cause large increases in pick forces required for a given penetration.

(17) When new, the wedge bit is more efficient than a point-attack bit, but as wear progresses, point-attack bits quickly become more efficient, and may actually experience a reduction in required pick forces.

(18) The use of water jets in conjunction with drag-bit cutters looks promising for extending the range of rock types suitable for drag-bit cutting, increasing efficiency, and reducing wear.

(19) The most efficient type of roller cutter, and the only one recommended, is the single disc cutter with a continuous edge.
(20) While roller-cutter forces do increase with increasing penetration, efficiency of cutting also improves. No limit to this effect has been found, indicating depths of cut should be the maximum allowed by cutter-bearing capacity.

(21) As for drag-bit cutters, spacing was found to have a dramatic effect on cutting efficiency of roller cutters. There is an optimum range of cutter spacing related to the achievable penetration.

(22) Roller-cutter edge angle affects penetration, and therefore, efficiency. Strength and wear considerations will, however, probably dictate the choice of edge angle.

(23) Roller-cutter diameter has only a small effect on cutter forces required for a given penetration. However, bearing capacity increases significantly with increased cutter diameter, thus higher penetrations are attainable, resulting in increased efficiency.

(24) Cutting velocity was seen to have little or no effect on roller-cutter performance, and need only be limited to prevent overheating.

(25) For roller cutters operating at efficient spacings, edge wear, unlike for drag-bit cutters, did not significantly affect cutter performance.

(26) The presence of foliation or other planes of weakness can greatly affect the cutting efficiency of both roller- and drag-bit cutting. The most efficient direction to cut is perpendicular to the planes of weakness, with up to a threefold reduction in forces observed in some cases for this direction of cut. Since oil shale is characterized by significant planes of weakness along its varve structure, a machine design that would take advantage of this preferential direction of cutting would be highly advantageous.

(27) Cutterhead shape has an effect on cutting efficiency and stability, with an optimum possible for each machine and cutter type.

(28) Full-face machines, where the cutterhead is in contact with the entire cross section to be cut, generally have a higher production rate. They
also have longer cutter life because the cutters are in constant contact with the rock, avoiding impact loads associated with continual reentry of cutters on partial-face machines.

(29) Partial-face machines, where a smaller cutterhead moves across the face, removing rock until the desired cross-section has been cut, have an advantage in being able to concentrate power on a reduced volume of rock, and the ability to be selective in the removal of various zones of rock (selective mining). Partial-face machines also are generally lighter and more flexible in application.

(30) Power requirements seem to dictate roller cutters for full-face applications, and drag bits for partial-face machines.

(31) New machine concepts being developed should combine the efficiency of a full-face machine with the flexibility and selective mining capability of partial-face machines.

(32) Theoretical and experimental means are available for predicting the effects of factors that influence a machine's performance. Using such predictive capability, and some basic tests on oil shale, it will be possible to optimize such machine characteristics as cutter type, cutter placement, cutterhead design, method of attack, power requirements, and overall efficiency.

(33) In addition to considering machine characteristics and capabilities, it is necessary to evaluate individual mining applications and the impacts of a machine and its support on the overall mining plan.
III. LABORATORY PHYSICAL PROPERTY AND CUTTING TESTS

Oil Shale Physical Properties

As part of this and other studies, extensive physical properties tests on oil shale were undertaken. The results of these tests reveal much about oil shale that is applicable to the utilization of mechanical excavation. In particular, data on the strength of oil shale and its variability applies directly to the selection of cutting tools and excavation systems. Compressive and shear strengths of oil shale place it in the crossover region between suitability for drag bit cutting and the requirement for roller cutters. The variability in strengths anticipated over a mining section force designs capable of efficient cutting in a wide range of material properties.

Several graphs are provided to summarize typical oil shale properties applicable to mechanical excavation. Figure 1 shows density variations over 731 samples. Note the curve is skewed toward higher densities which represents a natural upper bound determined by the density of barren marlstone. The distribution toward lower densities follows closely the oil yield for the samples, with richer grades showing reduced density. Brazilian tensile strength shows a very wide range of values as can be seen in Figure 2. Similarly uniaxial compressive strength can be seen to cover a wide range in Figure 3. It is obvious that any mechanical excavation system will have to deal with quite variable material properties. The Young's modulus and shear strengths as represented in Figures 4 and 6, show that oil shale can be a very tough rock, and this must be considered in selecting cutters and in designing machine configurations.

The physical properties results are also very useful for performance prediction using developed models for various cutting mechanisms. Work will continue on relating the physical properties to excavation systems and mine design.
FIGURE 1
OIL SHALE - DENSITY

MEAN = 2.16
STD DEV = 0.18
N = 731
FIGURE 2

OIL SHALE - BRAZILIAN TENSILE STRENGTH

MEAN = 1031.97
STD DEV = 473.17
N = 732
FIGURE 3

OIL SHALE - UNIAXIAL COMPRESSIVE STRENGTH

MEAN = 10876.19
STD DEV = 4798.79
N = 520
FIGURE 4

OIL SHALE - YOUNG'S MODULUS

MEAN = 2.17
STD DEV = 1.12
N = 519

PERCENTAGE

PSIX10**-6
FIGURE 5

OIL SHALE - POISSON'S RATIO

MEAN = 0.30
STD DEV = 0.12
N = 518
FIGURE 6

OIL SHALE - MULTIFAILURE TRIAXIAL SHEAR STRENGTH

Mean = 3464.29
Std Dev = 1526.04
N = 131
Linear Cutting Tests

To determine the effect of direction of cut, and to evaluate various cutting tools, several tests were performed on oil shale of approximately 30 gpt using the full-scale linear cutting machine available at the Earth Mechanics Institute, Colorado School of Mines. Cutters used included a Sandvik long shank conical bit as used in trials at Colony oil shale mine, and a Robbins disc cutter with both a 75 degree cutting edge and a constant cross section type cutting edge. Three directions of cut relative to the bedding planes or varve structure were used for these tests. The main objective was to determine the effect of bedding direction on the cuttability of oil shale. A representation of the three directions is provided in Figure 7.

For each bedding direction, an extensive series of tests was undertaken both with conical bit and the disc cutter. Tests were carried out at various cutter spacings and penetrations while the cutting speed was held constant at 10 in/sec. Each test consisted of a series of four or five passes over the rock surface with the tool, with each pass containing an average of ten cuts. At the completion of each pass, the cuttings were collected for sieve analysis. Visual observations were made of the chipping mechanism during cutting.

The results of the linear cutting tests are presented in Tables 1 through 6. Several pictures of the cutting tests are given in Appendix A. Although there is considerable scatter in the results due to the variability of oil shale (grade varied from 10 to 35 gpt with an average of 30 gpt), several trends are apparent. As expected, all three components of cutter forces; side, vertical and drag increase with increased penetration and/or spacing between cuts. A dramatic difference in cutting forces relative to direction being cut is evident, with direction number 1 being by far the easiest. This particular direction of cutting allows fracture propagation
along bedding planes, requiring minimal effort for the cutter to remove the interlying material between adjacent cuts. It is obvious that any design of mechanical equipment for mining oil shale should take advantage of this directional cutting property which oil shale exhibits. It is also apparent that pick cutters are more efficient for a given thrust, but require greater drag forces, meaning higher torque requirements on a machine.

To determine chip size distribution, sieve analyses were performed on the cuttings generated from each test. The results confirmed the observations and the conclusions drawn from cutter force data. As can be seen in Figures 8 and 9 cutting in direction 1 resulted in larger chips and fewer fines for both the Sandvik pick and the Robbins disc cutter. It was also found that the pick cutters generated larger chips and less fines, with more airborne dust, however. Figure 10 shows little effect of depth of cut on particle size distribution, and only a slight effect of doubling the spacing can be seen from Figure 11. The relative differences in size distributions, and therefore, efficiency, between pick cutter and disc cutter can be clearly seen in Figures 12 and 13. Where fines may be a problem, or if a specific muck size is desired, the selection of cutters and spacing may become critical.

An important factor which must be considered in the selection of an appropriate cutting tool for oil shale mining is the bit wear. Due to the limited amount of cutting, no quantitative analysis of bit wear could be accomplished from the tests conducted as part of this study. Although the conical bit is found to be more efficient in terms of cutting performance and chip size, it suffers a higher degree of wear than disc type cutters and therefore, may not be applicable for mechanical excavation of lower grade, harder oil shale formations. It is obvious that the bit wear should be included in any final analysis leading to the selection of a particular type of cutting bit to be utilized on a mechanical excavation system for oil shale mining.
LINEAR CUTTING TESTS FOR OIL SHALE

FIGURE 7

CUTTING DIRECTION #1

CUTTING DIRECTION #2

CUTTING DIRECTION #3

ROCK SAMPLE

CUTTER BIT

CUTTING SURFACE

BEDDING PLANES

EARTH MECHANICS INSTITUTE
COLORADO SCHOOL OF MINES
GOLDEN, COLORADO 80401
# TABLE 1

## OIL SHALE CUTTING

### TEST RESULTS

<table>
<thead>
<tr>
<th>CUTTING DIRECTION #1</th>
<th>SANDVIK CONICAL BIT</th>
<th>ANVIL POINT OIL SHALE</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>CUT SPACING (IN)</th>
<th>PENETRATION (IN)</th>
<th>SIDE FORCE (LB)</th>
<th>VERTICAL FORCE (LB)</th>
<th>DRAG FORCE (LB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.50</td>
<td>692</td>
<td>1922</td>
<td>1102</td>
</tr>
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<td>1.5</td>
<td>0.50</td>
<td>524</td>
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<tr>
<td>1.5</td>
<td>0.75</td>
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<td>854</td>
<td>2939</td>
<td>1632</td>
</tr>
<tr>
<td>3.0</td>
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<td>359</td>
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<td>1377</td>
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<tr>
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<td>0.75</td>
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<td>1773</td>
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<tr>
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<td>1.00</td>
<td>787</td>
<td>5475</td>
<td>3066</td>
</tr>
</tbody>
</table>

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GOLDEN, COLORADO 80401
TABLE 2

OIL SHALE CUTTING

TEST RESULTS

CUTTING DIRECTION # 1
SANDVIK CONICAL BIT
COLONY OIL SHALE

<table>
<thead>
<tr>
<th>CUT SPACING (IN)</th>
<th>PENETRATION (IN)</th>
<th>AVERAGE</th>
<th>SIDE FORCE (LB)</th>
<th>VERTICAL FORCE (LB)</th>
<th>DRAG FORCE (LB)</th>
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</thead>
<tbody>
<tr>
<td>3.0</td>
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<td>2036</td>
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<td>1.00</td>
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<td>6</td>
<td>4192</td>
<td>2112</td>
</tr>
</tbody>
</table>

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### TABLE 3

**OIL SHALE CUTTING**

**TEST RESULTS**

<table>
<thead>
<tr>
<th>CUT SPACING (IN)</th>
<th>PENETRATION (IN)</th>
<th>AVERAGE SIDE FORCE (LB)</th>
<th>AVERAGE VERTICAL FORCE (LB)</th>
<th>AVERAGE DRAG FORCE (LB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.25</td>
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<td>1770</td>
<td>852</td>
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<tr>
<td>1.5</td>
<td>0.35</td>
<td>96</td>
<td>2412</td>
<td>876</td>
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<td>1.5</td>
<td>0.50</td>
<td>457</td>
<td>3065</td>
<td>1299</td>
</tr>
</tbody>
</table>

**CUTTING DIRECTION # 2**

SANDVIK CONICAL BIT

ANVIL POINT OIL SHALE

---

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# Table 4

**OIL SHALE CUTTING**

**TEST RESULTS**

**CUTTING DIRECTION # 3**

**SANDVIK CONICAL BIT**

**AWIL POINT OIL SHALE**

<table>
<thead>
<tr>
<th>CUT SPACING (IN)</th>
<th>PENETRATION (IN)</th>
<th>SIDE FORCE (LB)</th>
<th>VERTICAL FORCE (LB)</th>
<th>DRAG FORCE (LB)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.75</td>
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<td>1.00</td>
<td>714</td>
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<td>2011</td>
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</tbody>
</table>

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GOLDEN, COLORADO 80401
## TABLE 5

### OIL SHALE CUTTING

#### TEST RESULTS

CUTTING DIRECTION # 2
12 IN. - 75° DISC CUTTER
ANVIL POINT OIL SHALE

<table>
<thead>
<tr>
<th>CUT SPACING (IN)</th>
<th>PENETRATION (IN)</th>
<th>AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SIDE FORCE (LB)</td>
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<tr>
<td>1.5</td>
<td>.25</td>
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<tr>
<td>1.5</td>
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<td>5119</td>
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<td>1190</td>
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<tr>
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<td>.50</td>
<td>2858</td>
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<tr>
<td>3.0</td>
<td>.50</td>
<td>3125</td>
</tr>
<tr>
<td>3.0</td>
<td>.50</td>
<td>1879</td>
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<tr>
<td>3.0</td>
<td>.50</td>
<td>1697</td>
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</table>

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<table>
<thead>
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<th>CUT SPACING (IN)</th>
<th>PENETRATION (IN)</th>
<th>SIDE FORCE (LB)</th>
<th>VERTICAL FORCE (LB)</th>
<th>DRAG FORCE (LB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>.25</td>
<td>320</td>
<td>13358</td>
<td>1281</td>
</tr>
<tr>
<td>3.0</td>
<td>.50</td>
<td>419</td>
<td>21362</td>
<td>3008</td>
</tr>
<tr>
<td>3.0</td>
<td>.75</td>
<td>403</td>
<td>32824</td>
<td>4638</td>
</tr>
</tbody>
</table>
FIGURE 8

LINEAR CUTTER SIEVE RESULTS

SANDVIK PICK

X = CUTTING DIRECTION # 1
SPACING 1.50"
PENETRATION .50"

O = CUTTING DIRECTION # 2
SPACING 1.50"
PENETRATION .50"

Δ = CUTTING DIRECTION # 3
SPACING 1.50"
PENETRATION .50"

ROCK SAMPLE
CUTTER BIT
CUTTING SURFACE
BEDDING PLANES

CUTTING DIRECTION # 1
10,000
1,000
100
10

CUTTING DIRECTION # 2
CUTTING DIRECTION # 3

MESH SIZE IN MICRONS
FIGURE 9
LINEAR CUTTER SIEVE RESULTS

ROBBINS DISK
x = CUTTING DIRECTION # 2
SPACING 3"
PENETRATION .25" (ANVIL)

ROBBINS DISK
o = CUTTING DIRECTION # 1
SPACING 3"
PENETRATION .25" (COLONY)

ROCK SAMPLE -L-
BEDDING PLANES

CUTTER BIT
CUTTING SURFACE

CUTTING DIRECTION # 1
CUTTING DIRECTION # 2

MESH SIZE IN MICRONS

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FIGURE 10

LINEAR CUTTER SIEVE RESULTS

SANDVIK PICK
x = CUTTING DIRECTION # 1
SPACING 1.50"
PENETRATION .50"

o = CUTTING DIRECTION # 1
SPACING 1.50"
PENETRATION .75"

A = CUTTING DIRECTION # 1
SPACING 1.50"
PENETRATION 1.00"

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FIGURE 11

LINEAR CUTTER SIEVE RESULTS

SANDVIK PICK

x = CUTTING DIRECTION # 1
SPACING 1.50"
PENETRATION .50"
o = CUTTING DIRECTION # 1
SPACING 3.00"
PENETRATION .50"

CUTTER BIT

CUTTING SURFACE

ROCK SAMPLE

BEDDING PLANES

CUTTING DIRECTION # 1

% CUMULATIVE RETAINED

MESH SIZE IN MICRONS

100,000 10,000 1,000 100 10
FIGURE 12

LINEAR CUTTER SIEVE RESULTS

SANDVIK PICK

x = SPACING 1.50"
PENETRATION .25"
CUTTING DIRECTION # 2

ROBBINS DISK

o = SPACING 1.50"
PENETRATION .25"
CUTTING DIRECTION # 2

CUTTER BIT
CUTTING SURFACE

ROCK SAMPLE
BEDDING PLANES
CUTTING DIRECTION # 2
FIGURE 13
LINEAR CUTTER SIEVE RESULTS

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GOLDEN, COLORADO 30401

SANDVIK PICK
X = CUTTING DIRECTION # 1
SPACING 3"
PENETRATION .75" (ANVIL)
ROBBINS DISK
O = CUTTING DIRECTION # 1
SPACING 3"
PENETRATION .75" (COLONY)

ROCK SAMPLE
CUTTER BIT
BEDDING PLANES
CUTTING DIRECTION # 1

% CUMULATIVE RETAINED
100
90
80
70
60
50
40
30
20
10
0
100,000 10,000 1,000 100 10
MESH SIZE IN MICRONS
Rotary Cutting Tests

As a culmination of this program, several tests were run in oil shale on the EMI drill rig using a boom miner cutterhead provided by Dosco. The large block of oil shale used was characteristically banded with grades of 10 to 40 gpt, and an average grade of 25 gpt. The sample was from the Mahogany Zone and should be fairly representative of the type of oil shale which would be cut in an actual underground oil shale mine. The cutterhead was fitted with Sandvik conical bits, same as those used in cutting trials performed in the Colony oil shale mine. The rapid cutting action of the head limited the number of tests that could be run, but several runs at various thrusts and rotation speeds were successful and provided some very interesting data. Table 7 shows the parameters measured and the tests run.

Machine operation was very smooth, and the data acquisition system worked perfectly. Samples of the data recorded are provided in Figures 14 and 15. It can be seen that the thrust can be held quite steady, and that penetration occurs very evenly with some stairstepping. The torque and RPM can be seen to oscillate around a mean as the picks alternately slip-stick while cutting the rock.

Tables 8, 9, and 10 summarize the data in terms of means, standard deviations, and inter-variable correlations. Pictures of the drill rig and the cutterhead are given in Appendix A. To provide a "feel" for the data, the distributions were plotted and are shown in Figures 16 through 27. These figures represent penetration, thrust, torque, and RPM for three different tests; tests varied from 15 to 30 RPM and 20,000 to 40,000 lbs. thrust. Data was collected at the rate of 10 data points per second. Total duration of the tests varied from 30 to 40 seconds. The shape of the distributions are as expected with the penetration being uniform and the other parameters having normal (bell shaped) form. Variability about the means is relatively small
and well within the expected noise limits for the tests. Variation is due to machine vibration and the electrical/mechanical control system itself.

The most important finding from these tests was the effect of thrust on cutting performance. At a low thrust of 20,000 lbs., barely any rock was cut as the thrust level was insufficient for individual bits to effectively penetrate oil shale. Increasing the thrust to 40,000 lbs. dramatically increased the penetration rate, indicating there is a critical thrust one must exceed to obtain efficient cutting. Below this critical thrust "GLAZING" occurs, a phenomenon which results in very little cutting accompanied with extensive heat build-up on the bits. This is exactly what was observed in previous field tests, where insufficient machine thrust resulted in glazing and rapid bit wear. The exact level of this threshold thrust will depend on the type, shape, cutters, and size of the machine being used. Current machine thrusting capabilities are considered inadequate, and modifications in machine weight or in anchoring mechanisms will be required. A more thorough analysis of individual cutter forces, penetration, and spacing effects should allow the development of relationships to predict the cutterhead forces required for efficient cutting for each machine type.

Another encouraging result of the laboratory tests was the excellent correlation between torque and applied thrust. Figure 28 shows this result and indicates a correlation coefficient of 0.95.

A test was attempted at 60,000 lbs. of thrust, with dramatic cutting rates, but torque drive motor power peaks apparently disrupted the computer, resulting in loss of cutting data. The unit performed well with no damage to the picks and very little heat build-up. It would appear that as large a depth of cut as possible is the most effective approach for both optimal penetration rates and reduced unit costs.
### Table 7

**Rotary Cutting Tests Performed:**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Machine Thrust</th>
<th>Cutterhead RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20,000 lbs.</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>40,000 lbs.</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>40,000 lbs.</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>60,000 lbs.</td>
<td>30</td>
</tr>
</tbody>
</table>

**Test Parameters Measured:**

- Thrust
- Torque
- Penetration
- RPM
FIGURE 14

Machine Thrust: 40,000 lbs.

Cutterhead RPM: 15
FIGURE 15

Machine Thrust: 40,000 lbs.
Cutterhead RPM: 15
Machine Thrust: 40,000 lbs.
Cutterhead RPM = 15

Number of Observations: 358
Number of Variables: 4
F-level for Inclusion: 1.00E-05
F-level for Deletion: 1.00E-05

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Correlation with Variable 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - Penetration</td>
<td>2.4294039E+01</td>
<td>1.0158316E+00</td>
<td>0.020118</td>
</tr>
<tr>
<td>1 - Thrust</td>
<td>3.5574429E+01</td>
<td>1.4068477E+00</td>
<td>-0.095864</td>
</tr>
<tr>
<td>2 - Torque</td>
<td>2.2614923E+00</td>
<td>2.2926547E-01</td>
<td>-0.419522</td>
</tr>
<tr>
<td>3 - RPM</td>
<td>1.2637653E+01</td>
<td>2.1844356E+00</td>
<td>1.000000</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Chan Vs Chan</th>
<th>Correlation Coef.</th>
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</thead>
<tbody>
<tr>
<td>(0) (1)</td>
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<tr>
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<td>0.174427</td>
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<td>0.020118</td>
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<tr>
<td>(1) (2)</td>
<td>0.382525</td>
</tr>
<tr>
<td>(1) (3)</td>
<td>-0.095864</td>
</tr>
<tr>
<td>(2) (3)</td>
<td>-0.419522</td>
</tr>
</tbody>
</table>

SY = 5.9649654E+01
TABLE 9

Machine Thrust: 40,000 lbs.
Cutterhead RPM = 30

Number of Observations: 330
Number of Variables: 4
F-level for Inclusion: 1.00E-05
F-level for Deletion: 1.00E-05

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Correlation with Variable 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - Penetration</td>
<td>2.8967804E+01</td>
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</tr>
<tr>
<td>1 - Thrust</td>
<td>3.3341087E+01</td>
<td>1.0813646E+00</td>
<td>-0.135659</td>
</tr>
<tr>
<td>2 - Torque</td>
<td>2.0146928E+00</td>
<td>1.5866214E-01</td>
<td>-0.352241</td>
</tr>
<tr>
<td>3 - RPM</td>
<td>2.8907360E+01</td>
<td>2.4413338E+00</td>
<td>1.000000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Vs Channel</th>
<th>Correlation Coef.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<tr>
<td>0</td>
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<td>0.008836</td>
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<tr>
<td>0</td>
<td>3</td>
<td>0.013583</td>
</tr>
<tr>
<td>1</td>
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<tr>
<td>1</td>
<td>3</td>
<td>-0.135659</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>-0.352241</td>
</tr>
</tbody>
</table>

SY = 6.6664688E+01
Machine Thrust: 20,000 lbs.
Cutterhead RPM = 15

Number of Observations: 403
Number of Variables: 4
F-level for Inclusion: 1.00E-05
F-level for Deletion: 1.00E-05

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SY = 3.3606434E+01
FIGURE 16

DRIG1: 15RPM: 40000LBS: SAMPLE = 0.1 SEC.

MEAN = 24.29
STD DEV = 1.02
N = 358
MIN = 22.24
MAX = 26.07
FIGURE 17

DRIG1: 15RPM: 40000LBS; SAMPLE=0.1 SEC.

MEAN = 35.47
STD DEV = 1.22
N = 350
MIN = 31.58
MAX = 41.95

THRUST X1000LBS

PERCENTAGE
FIGURE 18

DRIG1: 15 RPM; 40000 LBS; SAMPLE = 0.1 SEC.

MEAN = 2.25
STD DEV = 0.21
N = 350
MIN = 1.51
MAX = 3.04
FIGURE 19

DRIG1: 15RPM: 40000LBS: SAMPLE=0.1 SEC

MEAN = 12.56
STD DEV = 2.08
N = 354
MIN = 7.51
MAX = 19.85

Percentage

7.50  8.00  8.50  9.00  9.50  10.00  10.50  11.00  11.50  12.00  12.50  13.00  13.50  14.00  14.50  15.00  15.50  16.00  16.50  17.00  17.50  18.00
FIGURE 20

DRIG2: 30RPM; 40000LBS; SAMPLE = 0.1 SEC

MEAN = 28.97
STD DEV = 1.61
N = 330
MIN = 25.95
MAX = 31.91
FIGURE 21

DRIG2: 30RPM; 40000LBS; SAMPLE=0.1 SEC.

MEAN = 33.41
STD DEV = 0.85
N = 328
MIN = 24.79
MAX = 35.10
FIGURE 22

DRIG2: 30RPM; 40000LBS; SAMPLE=0.1SEC

MEAN = 2.01
STD DEV = 0.15
N = 328
MIN = 1.46
MAX = 2.59
FIGURE 23

DRIG2: 30RPM: 40000LBS: SAMPLE=0.1SEC

MEAN = 28.93
STD DEV = 2.41
N = 329
MIN = 21.86
MAX = 35.05
FIGURE 24

DRIG3: 15RPM; 20000LBS; SAMPLE=0.1SEC

MEAN = 32.00
STD DEV = 0.14
N = 403
MIN = 31.54
MAX = 32.32
FIGURE 25

DRIG3: 15RPM; 20000LBS; SAMPLE=0.1SEC

MEAN = 17.58
STD DEV = 0.25
N = 393
MIN = 16.29
MAX = 19.22
Figure 26

DRIG3: 15 RPM: 20000LBS: SAMPLE = 0.1 SEC

Mean = 1.15
STD DEV = 0.09
N = 390
MIN = 0.96
MAX = 1.68
FIGURE 27

DRIG3: 15RPM; 20000LBS; SAMPLE=0.1SEC

MEAN = 14.25
STD DEV = 1.22
N = 402
MIN = 10.99
MAX = 17.58
FIGURE 28

THRUST VS TORQUE FOR OIL SHALE

SLOPE = 0.059
YO = 0.109
C COEF = 0.949
IV. ECONOMIC EVALUATION

Objective

Mechanical boring machines are generally not used routinely in hard rock mining operations due to the initial capital investment and the lack of experience and acceptance. Oil shale will offer a good opportunity to show the economic potential of mechanical excavation. The objective of the economic evaluation was to develop preliminary evaluation criteria for comparing a mechanical excavation system to conventional drill and blast methods. This work is part of a continuing effort to improve the understanding of how mechanical excavation systems behave in a mining environment. The greatest potential for mechanical fragmentation machines will be in providing low cost mine access drifts from the production areas to the surface facilities.

Cost of providing development openings in oil shale will require the knowledge of many machine/rock parameters such as rock type, machine power, penetration rate, cutter life, maintenance schedule, etc. Capital investment, labor requirements, and project scheduling will all play an important role in defining the economics of the overall project.

Knowledge of the cost sensitivity of different project parameters will improve the overall success of any particular tunneling project if this information is incorporated into an effective management plan. Acknowledging the problems of defining reliable cost estimates for an untested machine in oil shale, this section gives some general guidelines for anticipated trends and problems plus the software needed to quickly reexamine the economics as new technology evolves.

Introduction

Despite the many advantages of using tunnel boring machines (TBM), drill and blast is normally preferred in most mining applications. The trade-offs between the two systems of rock fragmentation are numerous,
highly interactive, and tedious to compute manually. As part of this study, an attempt was made to integrate the theoretical equations for predicting the performance of a tunnel boring machine (TBM) with the necessary economic parameters for aiding in decision making. Of particular interest is the development of a software package developed for a desk top computer system enabling an individual to interactively change problem parameters quickly to learn the relative importance of user selected parameters. Graphic options also allow the engineer to quickly plot desired results. All the programs and software discussed in this report can be fully implemented on a microcomputer.

Several mechanical fragmentation models are available for implementation on large main frame computers. Some of the models are quite complex and detailed. The primary goal of the EMI cost model was to develop a model which could integrate the design parameters of the tunnel boring machine with the principle factors controlling the costs. Detail was of less importance than simplicity. No attempt was made to integrate the fragmentation system with, for example, the materials handling or ground support systems. As most openings in oil shale will be temporary in nature and due to the relative competence of the oil shale, the cost of ground support will be smaller than fragmenting the rock. In any case, the cost of ground support and material handling will be higher for a drill and blast system compared to mechanical fragmentation.

No two mining projects can be compared directly because of the large number of factors which must be considered in the design stages. However, the universal criteria used for comparative purposes between mining projects is normally rate of advance or cost. Such factors as labor costs, labor productivity, geologic uniqueness, and political environment will, at times, make even comparison of costs and advance rates meaningless.

The actual conditions existing at a particular site are the criteria which will dictate the machine design, rate of advance, and the economic
consequences. Site factors may be classified as follows:

- rock characteristics and properties,
- geologic conditions,
- tunnel geometry.

Predicting the maximum rate of advance of a tunnel boring machine will depend upon the following machine parameters:

- machine thrust,
- machine torque,
- machine RPM,
- cutter type and geometry,
- cutterhead geometry,
- cutter wear.

The cost of using a mechanical boring machine will depend upon how a machine functions in the geologic environment and what it costs in terms of labor, material, and equipment. No two operations will ever be equivalent, however, the factors which determine the system's productivity will be similar from one job to another. The principal factors that determine the overall project costs are:

- time required to complete project,
- capital investment,
- material and labor costs.

There is considerably more to driving entries with a tunnel boring machine than measuring a few rock properties, designing a machine, defining a few costs, and letting a computer program define the "best way." The intent of the technique discussed herein is not to replace the engineer, but rather to help him or her to be more productive by being able to quickly calculate alternative designs in a shorter time frame.

In selecting a tunnel boring machine not all design and cost factors are of equal importance, therefore engineering design efforts should be proportional
to their potential reduction in cost or improvement in benefit.

**Computer Models**

As part of this program, a series of computer programs have been developed for evaluating the economics of various mining subsystems, including:

1) fragmentation - drilling and blasting;
2) fragmentation - tunnel boring machine with disk cutters;
3) material handling - cyclical;
4) ground support;
5) ventilation;
6) subsystems design.

All of these programs are designed to stand alone, however, they may be used collectively to evaluate a total system. The tunnel boring machine fragmentation program only looks at the actual rock breakage and does not include the materials handling, ventilation, ground control and support subsystem.

The basic premise upon which the economic cost/performance was derived is the machine-rock performance equations developed at the Earth Mechanics Institute based on previous research in rock cutting. One may choose to ignore the predictive equations and enter directly a penetration rate and machine horsepower, however, this does eliminate one of the most important design portions of the model. Given in Appendix A at the conclusion of this report are the equations used for calculating penetration and horsepower used in this discussion.

Following is a list of the equations used in the economic model itself:

**Project life**

\[
T = \frac{TL}{p \times RPM \times Cl \times HR \times A \times U} + SU
\]

where

\[
T = \text{project life, (days)}
\]

\[
TL = \text{tunnel length, (length)}
\]

\[
SU = \text{time to set up machine, (days)}
\]
\[ p = \text{penetration rate, } \frac{\text{Length}}{\text{rpm}} \]

\[ \text{RPM} = \text{revolutions per minute} \]

\[ C_l = \text{conversion factor} \]

\[ \text{HR} = \text{hours worked/day} \]

\[ A = \text{TBM availability} \]

\[ U = \text{TBM utilization} \]

The product \( A \times U \times 100 \) should equal percent time machine is at maximum thrust

**Labor cost**

\[ LC = L \times HR \times T \]

where

\[ LC = \text{total labor cost for project} \]

\[ L = \text{labor cost/hr} \]

**Material costs**

\[ MT = CT + PT + M_1 \times TL + M_2 \times T \times HR \times A \times U \]

where

\[ MT = \text{total cost of materials for project} \]

\[ CT = \text{cutter cost, ($)} \]

\[ PT = \text{power costs ($)} \]

\[ M_1 = \text{cost of materials, ($/length)} \]

\[ M_2 = \text{cost of materials ($!/TBM) (cutting) hours} \]

and

\[ CT = \frac{CN \times CC \times T \times HR \times A \times U}{CL} \]

where

\[ CC = \text{cost of one cutter disk ($)} \]

\[ CL = \text{cutter life (hours)} \]

and

\[ PT = \frac{HP \times C2 \times PC \times T \times HR \times A \times U}{EF} \]
where

\[ \text{HP} = \text{horsepower} \]
\[ C2 = \text{conversion factor} \]
\[ PC = \text{power cost ($/kwh)} \]
\[ EF = \text{motor efficiency} \]

**Equipment costs**

\[ \text{TBMC} = \text{total cost of the machine for the project} \]

**Project cost per unit length:**

\[ \text{TCPF} = \frac{\text{TBMC} + \text{MT} + \text{LT}}{\text{TL}} \]

where

\[ \text{TCPF} = \text{total project cost per unit length} \]

**Problem Sensitivity**

Ability to change and rerun a problem quickly gives one the opportunity to investigate how small or large changes in specific parameters will affect the overall results. It should be remembered that any two projects will vary significantly from what is presented here; thus, generalizations should not be concluded from what is presented herein. All of the values used in the examples presented in this report are taken to be realistic in 1982 US dollars. They do not represent any particular project and are generated only for illustration purposes used in this report.

**Rock properties and penetration**

Figure 29 is a plot of the thrust versus penetration with a 10% variation in rock strength properties. Figure 30 is a plot of the horsepower requirements for a desired penetration. Of importance is the sensitivity of the penetration rate to variations in rock strengths. If, for example, in the problem given in Figure 1 at 200,000 lbs. of thrust, the rock strength drops 10% from 30,000 psi to 27,000 psi, then the penetration rate will increase from 2.30 ft/hr to 2.43 ft/hr. This represents an increase in penetration of 20%. It may be concluded that a 1% decrease in rock strength will yield a 2% increase...
FIGURE 29: PENETRATION RATE VS MACHINE THRUST

- Compressive Strength (PSI): 30000
- Shear Strength (PSI): 3000
- Cutterhead Dia. (IN): 84
- Number Cutters: 16
- Cutter Angle (Degrees): 90
- Cutter Diameter (IN): 12
- Cutterhead (RPM): 9
- Rock Variation (%): 10
FIGURE 30: H.P. VS PENETRATION RATE

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<th>Parameter</th>
<th>Value</th>
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<td>SHEAR STRENGTH (PSI)</td>
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<tr>
<td>CUTTERHEAD DIA. (IN)</td>
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<td>NUMBER CUTTERS</td>
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<td>CUTTER ANGLE (DEGREES)</td>
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<tr>
<td>CUTTER DIAMETER (IN)</td>
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<td>CUTTERHEAD (RPM)</td>
<td>9</td>
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<tr>
<td>ROCK VARIATION (%)</td>
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![Graph showing the relationship between CUTTERHEAD HORSEPOWER and PENETRATION RATE (FT/HR).]
in any calculation for the problem as defined in Figure 29. It should be obvious that care should be exercised when defining rock strength using the computer model.

Appendix B gives a set of computer plots for a variation of machine configurations.

**Problem parameters**

To illustrate how the model was used, Table 11 gives a set of user defined parameters used in this report to show how the various problem parameters interact one with another.

Following are the basic assumptions used to compile the data used in Table 11. In the following the abbreviation D & B is used to denote drilling and blasting.

**Basic conditions:**

only the fragmentation subsystem is considered, costs do not include:

- material handling
- ground support
- support services
- overhead, amortization, etc.

**Tunnel definition:**

- length: 20,000 ft.
- Shape: TBM - 12 ft. diameter - circular
  D&B - 10.6x10.6 ft. - rectangular
- geology: ideal

**Rock properties:**

- rock density: 2.3
- compressive strength: 15,000 psi
- shear strength: 1,500 psi
### Table II  Sample problem

#### *** INPUT ***

### *** GENERAL PARAMETERS ***
- **ROCK DENSITY**: 2.30
- **HOURS/DAY**: 24.00
- **DAYS/YEAR**: 255.0
- **TUNNEL LENGTH**
  - (FT): 200000
  - (DAYS): 30.0
- **TUNNEL DIAMETER**
  - (IN): 144.0
- **COMPRESS STREN (PSI)**: 15000
- **SHEAR STRENGTH (PSI)**: 1500

#### *** MACHINE PARAMETERS: ***
- **TOTAL NUMBER OF CUTTERS**: 24
- **CUTTER ANGLE (DEG)**: 90
- **DIAMETER OF CUTTER (IN)**: 17.5
- **RPM**: 8.0
- **MOTOR EFFICIENCY**: 0.90
- **THRUST (LBS)**: 960000
- **AVAILABILITY**: .80
- **CUTTER LIFE (HR)**: 500
- **MOTOR HOURS**: 6000

#### *** COST PARAMETERS ***
- **LABOR ($/HR)**: 210.00
- **CUTTER ($/EA)**: 325.00
- **MATERIAL ($/FT)**: 7.20
- **POWER ($/KW)**: 0.14
- **MACHINE ($)**: 2100000
- **MATERIAL ($/HR)**: 0.00

#### *** RESULTS ***

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<td>18.3</td>
<td>105.0</td>
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<tr>
<td>$/HR</td>
<td>210.0</td>
<td>113.5</td>
<td>651.4</td>
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<td>366001</td>
<td>2100000</td>
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- **ADVANCE FT/HR MAXIMUM**: 16.6
- **ADVANCE FT/HR AVERAGE**: 8.0
- **DAYS TO COMPLETE PROJECT**: 134.3
- **TOTAL TONS**: 162317
- **TOTAL MACHINE HOURS**: 1202
- **% MACHINE UTILIZED**: 20.0

**Conversions**
- 1 LB force = 4.45 Newtons
- 1 PSI stress = 6400 pascals
- 1 IN length = 2.54 centimeters
- 1 FT length = 0.305 meters
Machine characteristics:

**TBM:**
- 24 disk cutters
- 17.5 in. cutter diameter
- 90 degree cutting angle on cutter
- 960,000 lb. machine thrust
- 8 rpm
- 500 hours of cutter life
- 0.8 machine availability
- 0.6 machine utilization

**D&B:**
- 1.5 powder factor
- 7.2 ft. depth of round
- 7 hours to complete cycle
- 0.8 equipment availability
- 0.8 equipment utilization

Costs:

**equipment:**
- TBM - $2,100,000 (TBM only)
- D&B - $300,000 (drill jumbo)

**Materials:**
- TBM - $325 per cutter
  - $.14 per KWH
  - $7.20 per ft., misc.
- D&B - powder $0.50 per lb.
  - $7.20 per ft., misc.

**Labor:**
- TBM - $40/hour/man
  - 5 men for 15 shifts production
  - 9 men for 1 shift maintenance
- D&B - $40/hour/man
  - 2.5 men for production and maintenance

Equipment utilization

The importance of the rock strength upon penetration rate is perhaps better illustrated in Figure 31. Figure 31 shows the influence that rock strength of 10,000 psi, the penetration rate decreases rapidly. As is evident
THRUSt = 960000 LBS
NUMBER CUTTERS = 24
TBM DIAMETER = 12 FT

FIGURE 31: COMPARISON OF THEORETICAL PENETRATION RATES VERSUS ROCK STRENGTH
in this figure, the actual rates achieved under field conditions are approximately only 40% of the estimated theoretical penetration rates. This is not a totally unexpected result, because the actual time a machine is cutting is normally less than 50% of the time during a project life. Thus, a .05 point gain in machine utilization may be directly translated into a greater than 5% increase in rate of advance for most operations (especially if actual cutting time is less than 50%). For example, increasing machine cutting time from 25% to 30% will actually shorten the time of the tunneling project by 20%.

It should be remembered that these curves will be valid indicators only under the best of conditions. For example, with decreased rock strength ground control problems will most likely increase and become a limiting factor to the rate at which an opening can be successfully advanced. Rate at which material can be removed from the TBM must also be considered. Other environmental factors such as water, temperature, gases, etc. can pose problems which can significantly affect the advance rate of a mechanical excavator.

**TBM versus conventional**

Another area of concern to many decision makers is the trade-offs between tunnel boring machines and conventional drill and blasting. Figure 32 shows the cost per meter of driving a tunnel of varied lengths using the two methods. All factors being equal (this is not normally the situation) for tunnels of less than 20,000 ft. the actual cost per meter of advance is much cheaper using conventional drilling and blasting. As the length of excavation or tunneling increases, as would be true in a mining environment, TBMs are more cost effective. This is primarily due to the relationship between capital investment and operating costs for the two alternatives. This fact is graphically shown in Figure 33. If the cost of capital is high, one may wish to take what is presented here one step further by considering the cash flow.
Figure 32: Cost comparison for conventional mining and tunnel boring machine (TBM)
FIGURE 33: COST SENSITIVITY COMPARISON OF CONVENTIONAL VERSUS MECHANICAL FRAGMENTATION
Parameter sensitivity

If each variable is allowed to change by a fixed quantity and the problem rerun each time, we may get an idea of those factors which have the greatest impact on the overall results. Using the parameter values given in this report, a 10% parameter change (taken one at a time) will yield a reduction in overall project cost between a maximum of $210,000 and a minimum of $1,600. Ranking the parameters from most important to least impact on the results gives the plot shown in Figure 34. As illustrated by this example, more effort should be allocated to the cost assumed for the tunnel boring machine itself compared to, for example, the rock properties. Relatively speaking, the cost of the tunnel boring machine is 4.47 times as important as the rock properties.

Verification of Results

Verification of the penetration equation has been tested on red granite, marble, and limestone in the laboratory and under field conditions and agreement has been between 5 to 10% between predicted and actual. Expected correlation for the costs then should be within plus or minus 20% depending upon the experience of the user. Predicting costs is an art. How close a prediction will be to reality for a particular project will depend upon the validity of the assumptions.

Appendix C contains a statistical evaluation of some data collected by RMC, Inc. In a 1971 study titled "Tunneling Cost Analysis," of interest is the large variation in costs between projects. However, there is a definite relationship between the rock properties, tunnel length, tunnel diameter, and costs. Interpretation of results is left to the reader.

Summary

The basic economic model discussed in this report is an inexpensive tool based upon sound engineering for testing alternative machine designs in an
FIGURE 34: RELATIVE SENSITIVITY OF PROBLEM PARAMETERS

Factors ranked by relative sensitivity represents 10% change in parameter.
oil shale environment. In the design stages, these programs can give insight into where the major efforts are going to have to be placed to improve advance rates and/or reduce costs. Comparison of several different possible changes in an existing mining operation can quickly be evaluated on a computer to rank the alternative changes based upon their potential economic benefit.

Economics do suggest that TBMs can provide a lesser cost fragmentation system when compared to drilling and blasting in oil shale. There are still a lot of unknowns, such as the economies of scale to be gained for large oil shale mines, the wear of cutter disks in oil shale, the machine utilization in a working environment, etc.
V. CONCLUSIONS

A number of conclusions can be drawn from this investigation relative to mechanical excavation applied to oil shale.

1. The physical properties of oil shale are fairly well understood. As applies to mechanical excavation, the range of strengths observed places oil shale in the region of crossover between suitability for drag bit cutters and the requirement for roller cutters. Also the variability in physical properties over an anticipated mining section demand that an oil shale excavator be able to operate over the wide range of rock properties present. An understanding of the rock physical properties also means that existing performance prediction models can be used effectively to evaluate mechanical excavation systems and estimate their production rates.

2. Linear cutting tests were effective in determining the forces required to efficiently cut oil shale. The effects of cutting direction were dramatic and must be considered in estimating production and in machine design. The ease of cutting in a direction perpendicular to the bedding or varve structure suggests a machine designed to take advantage of this directional property would represent a significant improvement in efficiency. From these preliminary tests it appears drag bit type cutters are more efficient in terms of fragment size and minimum fines. Disc cutting has the advantage of less dust and longer cutter life.

3. Rotary Cutting tests in oil shale using a Dosco boom head with long shank conical bits demonstrated that an excavation system can be successfully evaluated in the laboratory. Excellent correlations between machine parameters and performance were observed. The laboratory tests support the conclusion that a minimum thrust or force per cutter is required for effective cutting. This is borne out by experiences in the field where roadheader type machines have been tried in oil shale. Generally the light weight of the machines have
prevented sufficient thrust to the cutters to allow efficient cutting. This results in glazing of the oil shale, excess heat buildup and rapid wear of the cutters. It is evident that as deep a cut as possible needs to be attained resulting in higher production and lower cutter costs.

4. An evaluation of mechanical excavation applied to oil shale revealed a significant need and many potential benefits. It is felt there are two distinct areas of applicability, development and production mining, which must be considered separately. Mechanical excavation also offers potential benefits to an open pit oil shale mining operation.

Full-face machines offer higher production rates, but lack of mobility may restrict their application only to development. Partial-face machines, such as roadheaders, are generally very maneuverable but may be limited in attainable production rates. New machine concepts being developed should combine the efficiency of a full-face machine with the flexibility and selective mining capability of partial-face machines.

A technique was developed for ranking machine capabilities and performance to determine the relative applicability to oil shale mining. Considering current technology, tunnel boring machines, slot machines, and rectangular boring machines appear to be best suited for the long drives envisaged for development work. In terms of immediate application, full-face machines using disc cutters remain the best choice because of their high production rates and proven concept. For future applications in development work, full-face machines still remain a good choice, but anticipated improvements in machine design and size also make the boom-type miner attractive for development. For a production application using existing technology, boom-type miners, continuous miners, and the mobile miner appeared most favorable. These machines ranked only marginally above drill and blast, suggesting the possibility that a synergistic combination of mechanical excavation with drill and blast may, for the present, be an optimum approach. The future potential for mechanical excavation in
production is excellent. As larger, more specific machines are developed for production, mechanical excavation is expected to dominate. Boom-type miners, continuous miners, and the mobile miner have the best potential, mainly because of mobility and flexibility. Two full-face machines, the rectangular boring machine and the slot machine, show considerable potential as mining systems adapt to take advantage of their high production rates and low costs, while compensating for their reduced mobility.
VI. RECOMMENDATIONS

The conclusions of this study are felt to be valid for the information available from literature review and the results of laboratory cutting tests. Yet most of the machines evaluated have never cut oil shale. It is therefore, felt that cutting performance of each system evaluated should be verified through additional laboratory tests of various cutters and cutting patterns before any final conclusions are drawn as to the best mechanical excavation systems to pursue for their potential application to oil shale mining. Toward this end, the following areas are recommended for further research:

*1. Linear cutting test of various cutters at different spacing and penetrations at several bedding orientations.

*2. Full scale laboratory tests on drill rig and the rotary cutting machine to evaluate cutterhead design (shape, spacing, muck handling, temperature, wear, power, forces, etc.).

3. Determining design principles for optimum performances.

4. Estimate productivity and applicability.

5. Economic comparisons.

6. New mine design approaches to take advantage of the benefits of mechanical excavation.

7. Investigate application of water jets or other assisting mechanisms.

8. Total system evaluation to include cutting, material handling, retorting, disposal, backfill, roof and pillar stability and overall economics.

*These equipment are currently available at the Earth Mechanics Institute, Colorado School of Mines.
VII. REFERENCES


APPENDIX A

Pictures of laboratory cutting tests in oil shale
Large Linear Cutting Machine Used for Testing Conical Bit and Disc Cutter in Oil Shale.
Conical Bit Mounted on Linear Cutter.
Conical Bit Testing for Oil Shale Bedding Direction No. 1.
Chips Produced from Cutting in Bedding Direction No. 1.
Chips Produced from Conical Bit Tests for Bedding Direction No. 1
Disc Cutter Testing for Bedding Direction No. 1.
Penetration .35
Spacing 1.50
Pick Perpendicular to Bedding Plane

Rock Surface Produced by Conical Bit in Bedding Direction No. 2
Typical Chips for Bedding Direction No. 2 (Conical Bit)
Disc Cutter Testing in Bedding Direction No. 2
Typical Chips for Bedding Direction No. 2 (Disc Cutter)
Conical Bit Testing for Bedding Direction No. 3
Rock Surface for Bedding Direction No. 2 (Conical Bit)
Laboratory Drilling Rig Used for Testing Dosco Roadheader Cutting Head.
Oil Shale Sample Placed on the Drill Rig.
The Roadheader Cutting Head with Conical Bits.
Operation of Roadheader Cutting Head in Oil Shale.
View of Rock Surface Created by the Roadheader Cutting Head Dressed with Conical Bits.
APPENDIX B

The theoretical relationship for calculating the penetration per revolution for a sharp disc cutter.
The theoretical relationship for calculating the penetration per revolution for a sharp disc cutter based upon work done at the Earth Mechanics Institute, Colorado School of Mines, is as follows:

\[ p = t^2 = (X + Y)^2 \]

where \( t = X + Y \), and

\[ X = \left( -\frac{b}{2} + \sqrt{\frac{b^2}{4} + \frac{a^3}{27}} \right) ^{1/3} \]
\[ Y = \left( \frac{b}{2} - \sqrt{\frac{b^2}{4} + \frac{a^3}{27}} \right) ^{1/3} \]

\[ a = \frac{2 \tau s}{\frac{4}{3} C - 4 \tau \tan \alpha / 2} \cdot D^{1/2} \cdot \tan \alpha / 2 \]
\[ b = \frac{\frac{4}{3} C - 4 \tau \tan \alpha / 2}{\frac{4}{3} C - 4 \tau \tan \alpha / 2} \cdot D^{1/2} \cdot \tan \alpha / 2 \]

where definition of this variable is as follows:

\( VF \) = vertical force on the cutter (force)  
\( C \) = rock uniaxial compressive strength (stress)  
\( \tau \) = rock unconfined shear strength (stress)  
\( D \) = cutter diameter (length)  
\( \alpha \) = cutter included edge angle (degrees)  
\( s \) = spacing of cuts (length)  
\( p \) = cutter penetration (length)

The theoretical equation used to calculate horsepower is expressed as follows:

\[ HP = \frac{TQ \cdot RPM \cdot 2 \cdot \pi}{C3} \]

where

\[ TQ = RF \cdot CN \cdot TD / C4 \]
\[ RF = VF \cdot \tan \beta \]
\[ \tan \beta = \frac{(1 - \cos \phi)^2}{\phi - \sin \phi \cos \phi} \]

and

\[ \phi = \text{ArcCos} \left( \frac{R - P}{R} \right) \]
\[ R = CD/2 \]

where

\( HP \) = horsepower  
\( C3 \) = conversion factor  
\( TQ \) = torque (length-force)  
\( RF \) = rolling force (force)  
\( CN \) = number of cutters  
\( TD \) = diameter of cutterhead (length)  
\( C4 \) = conversion factor  
\( \tan \beta \) = cutting coefficient  
\( R \) = radius of cutterhead (length)  
\( CD \) = cutterhead diameter (length)  
\( RPM \) = revolution per minute
Penetration vs Machine Thrust for Varied Machine/Rock Parameters:

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<thead>
<tr>
<th>Machine Diameter (ft)</th>
<th>Number Cutters</th>
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<th>RPM</th>
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PENETRATION RATE VS MACHINE THRUST

- Compressive Strength (PSI): 10000
- Shear Strength (PSI): 1666
- Cutterhead Dia. (IN): 120
- Number Cutters: 15
- Cutter Angle (Degrees): 90
- Cutterhead Diameter (IN): 15
- Cutterhead (RPM): 8
PENETRATION RATE VS MACHINE THRUST

<table>
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<tr>
<th>Parameter</th>
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<td>Cutterhead RPM</td>
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Graph showing the relationship between penetration rate (feet/hr) and machine thrust (lbs x 10^3).
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<td>Cutterhead RPM</td>
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**Graph:**

- **Penetration Rate (FT/HR)**
- **Machine Thrust (LBS) x 10^3**

- Values range from 100 to 600.
PENETRATION RATE VS MACHINE THRUST

COMPRESSIVE STRENGTH (PSI) : 10000
SHEAR STRENGTH (PSI) : 1666
CUTTERHEAD DIA. (IN) : 240
NUMBER CUTTERS : 30
CUTTER ANGLE (DEGREES) : 90
CUTTERHEAD DIAMETER (IN) : 15
CUTTERHEAD (RPM) : 5
PENETRATION RATE VS MACHINE THRUST

COMPRESSIVE STRENGTH (PSI) : 15000
SHEAR STRENGTH (PSI) : 2500
CUTTERHEAD DIA. (IN) : 240
NUMBER CUTTERS : 30
CUTTER ANGLE (DEGREES) : 90
CUTTERHEAD DIAMETER (IN) : 15
CUTTERHEAD (RPM) : 5

MACHINE THRUST (LBS) x 10^4
PENETRATION RATE VS MACHINE THRUST

COMPRESSIVE STRENGTH (PSI) : 20000
SHEAR STRENGTH (PSI) : 3333
CUTTERHEAD DIA. (IN) : 240
NUMBER CUTTERS : 30
CUTTER ANGLE (DEGREES) : 90
CUTTERHEAD DIAMETER (IN) : 15
CUTTERHEAD (RPM) : 5
PENETRATION RATE VS MACHINE THRUST

COMPRESSIVE STRENGTH (PSI) : 10000
SHEAR STRENGTH (PSI) : 2500
CUTTERHEAD DIA. (IN) : 120
NUMBER CUTTERS : 15
CUTTER ANGLE (DEGREES) : 90
CUTTERHEAD DIAMETER (IN) : 15
CUTTERHEAD (RPM) : 8

MACHINE THRUST (LBS) $\times 10^3$

[Graph showing the relationship between penetration rate (ft/hr) and machine thrust (lbs)]
PENETRATION RATE VS MACHINE THRUST

- Compressive Strength (PSI): 10000
- Shear Strength (PSI): 3333
- Cutterhead Dia. (IN): 120
- Number Cutters: 15
- Cutter Angle (Degrees): 90
- Cutterhead Diameter (IN): 15
- Cutterhead (RPM): 8

Graph showing the relationship between penetration rate (ft/hr) and machine thrust (lbs x 10^3).
PENETRATION RATE VS MACHINE THRUST

COMPRESSIVE STRENGTH (PSI) : 15000
SHEAR STRENGTH (PSI) : 2500
CUTTERHEAD DIAM. (IN) : 120
NUMBER CUTTERS : 15
CUTTER ANGLE (DEGREES) : 90
CUTTER DIAMETER (IN) : 15
CUTTERHEAD (RPM) : 8
PENETRATION RATE VS MACHINE THRUST

COMPRESSIVE STRENGTH (PSI) : 15000
SHEAR STRENGTH (PSI) : 2500
CUTTERHEAD DIA. (IN) : 120
NUMBER CUTTERS : 30
CUTTER ANGLE (DEGREES) : 90
CUTTERHEAD DIAMETER (IN) : 15
CUTTERHEAD RPM : 8
PENETRATION RATE VS MACHINE THRUST

- Compressive Strength (PSI): 15000
- Shear Strength (PSI): 2500
- Cutterhead Dia. (in): 120
- Number Cutters: 15
- Cutter Angle (Degrees): 75
- Cutterhead Diameter (in): 15
- Cutterhead (RPM): 8

Graph showing the relationship between Penetration Rate (ft/hr) and Machine Thrust (lbs x 10^3).
PENETRATION RATE VS MACHINE THRUST

- Compressive Strength (PSI): 15000
- Shear Strength (PSI): 2500
- Cutterhead Dia. (IN): 120
- Number Cutters: 30
- Cutter Angle (Degrees): 75
- Cutterhead Diameter (IN): 15
- Cutterhead (RPM): 8
PENETRATION RATE VS MACHINE THRUST

COMPRESSIVE STRENGTH (PSI) : 10000
SHEAR STRENGTH (PSI) : 1650
CUTTERHEAD DIA. (IN) : 480
NUMBER CUTTERS : 60
CUTTER ANGLE (DEGREES) : 90
CUTTERHEAD DIAMETER (IN) : 15
CUTTERHEAD (RPM) : 3
APPENDIX D

COST EVALUATION

D-1 - Tunneling Cost Data
D-2 - Correlations Between Tunnel Parameters and Cost
D-3 - Distribution of Tunneling Costs (1970): Total
D-4 - Distribution of Tunneling Costs (1970): Excavation
D-5 - Distribution of Tunneling Costs (1970): Support
D-6 - Distribution of Tunneling Costs (1970): Lining
<table>
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<th>Project</th>
<th>Rock RQD</th>
<th>Tunnel Length x1000 Ft</th>
<th>Tunnel Volume x1000 YD.³</th>
<th>YD.³/FT. Advance</th>
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## TUNNELING COST DATA (1)

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<th>Project</th>
<th>Rock RQD</th>
<th>Tunnel Length x1000 FT.</th>
<th>Tunnel Volume x1000 YD.³</th>
<th>YD.³/FT. Advance</th>
<th>Excavation</th>
<th>Support</th>
<th>Lining</th>
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## Correlation Between Tunnel Parameters and Cost (1)

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<th>Tunnel Volume x1000 YD.³</th>
<th>YD.³/FT. Advance</th>
<th>Excavation Cost $/FT.</th>
<th>Support Cost $/FT.</th>
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(1) Source: Tunneling Cost Analysis - RPT FRA-RT-71-73, 1971

(2) 100 implies 100% total variance explained

   0 implies 0% total variance explained
D-3: DISTRIBUTION OF TUNNELING COSTS (1970): TOTAL

TOTAL COST

MEAN = 768.68
STD DEV = 613.78
N = 28
MIN = 154.00
MAX = 2428.00

$/FT (1970) x 10^1

EXCAVATION COST

- Mean = 434.92
- Std Dev = 291.31
- N = 28
- Min = 88.00
- Max = 1177.00

**SUPPORT COST**

| MEAN   | 138.38 |
| STD DEV | 228.86 |
| N       | 26     |
| MIN     | 0.00   |
| MAX     | 1146.00 |

$\$/FT (1970) $\times 10^1$

LINING COST

MEAN = 195.88
STD DEV = 208.58
N = 28
MIN = 5.00
MAX = 789.00
APPENDIX E

Minutes of Conference on "Mechanical Excavation of Oil Shale" held at the Earth Mechanics Institute, Colorado School of Mines on May 25, 1982.
<table>
<thead>
<tr>
<th>Name</th>
<th>Company</th>
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<tbody>
<tr>
<td>Gene Grossman</td>
<td>Mobil Oil Corporation Mining &amp; Coal Division</td>
<td>(303) 628-6369</td>
</tr>
<tr>
<td></td>
<td>P. O. Box 17772</td>
<td></td>
</tr>
<tr>
<td></td>
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<tr>
<td>Warren Johnson</td>
<td>Mobil Research &amp; Development Corp.</td>
<td>(214) 333-6155</td>
</tr>
<tr>
<td></td>
<td>P. O. Box 900</td>
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<tr>
<td></td>
<td>Dallas, TX 75221</td>
<td></td>
</tr>
<tr>
<td>Larry Snyder</td>
<td>Harrison Western Corp. 770 Simms Street</td>
<td>(303) 232-0363</td>
</tr>
<tr>
<td></td>
<td>Golden, CO 80401</td>
<td></td>
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<tr>
<td>Warren Harrison</td>
<td>Harrison Western Corp. 770 Simms Street</td>
<td>(303) 232-0363</td>
</tr>
<tr>
<td></td>
<td>Golden, CO 80401</td>
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<tr>
<td>David David</td>
<td>Harrison Western Corp. 770 Simms Street</td>
<td>(303) 232-0363</td>
</tr>
<tr>
<td></td>
<td>Golden, CO 80401</td>
<td></td>
</tr>
<tr>
<td>James L. Lane</td>
<td>Mobil Research &amp; Development Corp. Engineering Department</td>
<td>(303) 628-6089</td>
</tr>
<tr>
<td></td>
<td>P. O. Box 17772</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Denver, CO 80217</td>
<td></td>
</tr>
<tr>
<td>Charles H. Rich</td>
<td>Mobile Research &amp; Development Corp. Engineering Department</td>
<td>(303) 628-6038</td>
</tr>
<tr>
<td></td>
<td>P. O. Box 17772</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Denver, CO 80217</td>
<td></td>
</tr>
<tr>
<td>A. H. Scrymgeour</td>
<td>Mobil Oil Corporation P. O. Box 17772</td>
<td>(303) 628-6377</td>
</tr>
<tr>
<td></td>
<td>Denver, CO 80217</td>
<td></td>
</tr>
<tr>
<td>John N. Edl, Jr.</td>
<td>DOE/LETC Box 3395, University Station</td>
<td>(307) 721-2234</td>
</tr>
<tr>
<td></td>
<td>Laramie, WY 82071</td>
<td></td>
</tr>
<tr>
<td>Wilbur I. Duvall</td>
<td>8820 Dover Circle</td>
<td>(303) 233-0508</td>
</tr>
<tr>
<td></td>
<td>Lakewood, CO 80226</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Company/Address</td>
<td>Phone</td>
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<tr>
<td>B. C. Cummings</td>
<td>Phillips Petroleum, Box 3209, Englewood, CO 80155</td>
<td>(303) 741-3049</td>
</tr>
<tr>
<td>Milton Head</td>
<td>Head Development, Inc., P. O. Box 2038, Milan, NM 87021</td>
<td>(505) 285-4231, (505) 287-3496</td>
</tr>
<tr>
<td>William E. Hawes</td>
<td>Sohio Shale Oil Co., 50 S. Main, Ste. 930, Salt Lake City, UT 84144</td>
<td>(801) 328-3700</td>
</tr>
<tr>
<td>Wilfred S. Streeter</td>
<td>Exxon Company, USA, Colony Shale Oil Project, Box 440342, Aurora, CO 80015</td>
<td>(303) 695-2297</td>
</tr>
<tr>
<td>David A. Weiss</td>
<td>Tosco Corporation, 11100 E. Bethany Drive, P. O. Box 441464, Aurora, CO 80014</td>
<td>(303) 696-2781</td>
</tr>
<tr>
<td>Iain McKinlay</td>
<td>The Dosco Corporation, 7653 E. 47th Ave., Dr. 'H', Denver, CO 80216</td>
<td>(303) 321-5597</td>
</tr>
<tr>
<td>Larry Pyeatt</td>
<td>Union Oil Company, 2777 Cross Roads Blvd., Grand Junction, CO 81501</td>
<td></td>
</tr>
<tr>
<td>Thomas L. Watson</td>
<td>Cathedral Bluffs Shale Oil Company, P. O. Box 2687, Grand Junction, CO 81502</td>
<td>(303) 244-3102</td>
</tr>
<tr>
<td>Jim Friant</td>
<td>The Robbins Company, 7615 So. 212th Street, Box C8027, Kent, WA (98031)</td>
<td>(206) 872-0500</td>
</tr>
<tr>
<td>Levent Ozdemir</td>
<td>Colorado School of Mines, Earth Mechanics Institute, Golden, CO 80401</td>
<td>(303) 273-3419</td>
</tr>
<tr>
<td>Russell Miller</td>
<td>Colorado School of Mines, Earth Mechanics Institute, Golden, CO 80401</td>
<td>(303) 273-3404</td>
</tr>
<tr>
<td>Bill Sharp</td>
<td>Colorado School of Mines, Earth Mechanics Institute, Golden, CO 80401</td>
<td>(303) 273-3404</td>
</tr>
<tr>
<td>Darlene Pearse</td>
<td>Colorado School of Mines, Earth Mechanics Institute, Golden, CO 80401</td>
<td>(303) 273-3525</td>
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OPENING REMARKS AND INTRODUCTION

Dr. Ozdemir welcomed those attending the conference, introduced EMI staff and requested guests to give their name and company represented. Dr. Ozdemir stated that the purpose of the meeting is to present information on current work performed by Earth Mechanics Institute (EMI), as well as presentations by manufacturers for development of mechanical excavation technology for oil shale mining.

The application of mechanical excavation technology to oil shale does have significant potential. It is our intent to brief you on current work and receive your input as to the future direction of work related to this research and development effort.

EMI Staff will make a presentation on work the Institute is doing for DOE, followed by presentations by the manufacturers represented. The afternoon session will be devoted to a group discussion welcoming comments and suggestions relating to future mechanical excavation of oil shale. At the conclusion of this discussion, visitors are invited to visit EMI laboratories and view the linear cutting tests in oil shale.

EMI has been doing research and development work in mechanical excavation over the last 10 years, the last several years involved oil shale, a DOE preliminary study related to the technical and economic feasibility of applying mechanical excavation methods for production and development work in oil shale.
Dr. Ozdemir discussed the oil shale cutting work being performed at EMI under funding from DOE. Tests conducted to date include investigations of bedding effects on cutting performance and chip size using both drag and disc type cutters. The results showed a significant effect of bedding orientation on cutting forces and chip sizes. Best cutting performance was obtained when the bedding was parallel to the cutting surface (Case No. 1). He suggested that a machine designed to cut oil shale should take advantage of this effect to realize optimal performance in terms of production rate and excavation costs.

Dr. Miller of EMI discussed the results of chip size distributions for cutting tests performed in oil shale from Anvil Points and Colony mines. The bedding orientation was found to have a dramatic effect on chip sizes. Larger size cuttings were obtained when oil shale was cut perpendicular to bedding (Cutting Direction No. 1).

Mr. Sharp briefly discussed an ongoing resource evaluation project for the Piceance Basin in Colorado. Due to funding and organizational changes in DOE, this study is being terminated with emphasis to be placed on the economics of mechanical fragmentation of oil shale. As part of the new scope of work EMI will be working with the Los Alamos Laboratories to help them prepare and run the "Oil Shale Mining Economics Model" developed by Ketron. Mr. Sharp also reviewed the development and capabilities of EMI's microcomputer which is capable of producing interactive graphics for data reduction and analysis.
Mr. Friant stated that Robbins Company has been involved in mechanical excavation since 1952. He said he would discuss, "what we have learned about rock cutting in general and how it can be applied to oil shale; the present status of rock cutting technology, how we got there and how to make this technology applicable to your industry."

Mr. Friant began with "mining" as far back as 12,000 B.C., touched on the Black Powder era (the Continental Railroad was the last project using black powder); the Hoosak Tunnel in Massachusetts was the first project to use nitroglycerin based explosives; drilling and blasting came to forefront in the 20th Century. We are now looking more at mechanical mining techniques and getting away from explosives.

A slide of Col. Beaumont's machine used for the English Channel Tunnel was shown.

Robbins started making machines with picks but limitations became apparent when cutting harder rock formations. First success in cutting hard rock was achieved in 1956 with the machine using both discs and picks. The last machine combining both picks and discs was delivered in 1974. Discs reduce torque and will improve life of the cutter and thus the cost. (Slide presentation of various sizes of machines which have been developed). The disc cutter came into being and was used a long time before science caught up to it. Robbins does not make any cutter with spacing less than 1 1/2" (carbide buttons). Excavation power is related to rock hardness; the curve falls off in soft rock (coal).

Mechanical excavation seems to be the way mining technology will go as its economic feasibility approaches that of explosives.
PRESENTATION - Larry Snyder, Harrison Western

Mr. Snyder discussed the new developments at Harrison Western. Harrison Western primarily develops cutters for shaft sinking and tunnelling machines. We recently set up an engineering group to design specialized mining machinery. Three research projects are currently underway: 1) a conceptual model of blind shaft machine; 2) a machine developed to drive rectangular drifts; and 3) a circular tunnel boring machine that can turn 50' radius, making it more maneuverable.

Two models were on display at the conference: 1) a shaft sinking machine which does not cut full face; 2) a rectangular machine which does not cut a true rectangular shape, but cuts both face edge and roof simultaneously. Some development work needs to be done before these machines become a reality. The problem is not cutting the rock, but removing the rock.

PRESENTATION - William Streeter, Exxon (Substituting for Iain McKinlay)

Mr. Streeter spoke briefly of the results of cutting trials in the Exxon Colony mine using the Dosco twin-boom cutting machine. The machine cut over 660 tons of rock, and advanced 500 ft. during tests. Overall machine utilization was 54%. The machine cut less than 100 hours. The average cutting rate was 96 tons/hour; the peak cutting rate was 140 tons/hour. Dust level is of high concern, as well as the particle size distribution. We tried cutting in both directions with respect to bedding. Water sprays on the machine ran about 10 gal/min. Cutting costs were higher than we had hoped for. We are very optimistic for this type machine and believe it will be cheaper than drill and blast.

GROUP DISCUSSION

Mobil - A. H. Scrymgeour

As far as Mobil is concerned, we are further behind than most other
companies. We are looking and evaluating, and have not yet selected a system of mining. We are looking at other companies, to see what they are doing and profit by their experience. We do not know what to do about mechanical mining. We do want to keep up with new developments. We are in the Mahogany zone, but have not selected a retort.

Union Oil - Larry Pyeatt

Next year hope to be producing 15,000 tons per day. The budget looks good for next year. We are going to go with drilling and blasting using front end loaders to load 50 ton off-highway trucks. We are mining 27' x 50' and coming out with a panel pickup to 33' to make 60'. Next year we hope to start to retort at 1/10 capacity.

Tosco - Dave Weiss

Tosco has been a supporter of mechanical mining concepts for a long time. We don't think it has reached its full potential. Mechanical mining has some current promise in today's time frame. We believe we are closer than ever before to reaching full potential. I cannot add more to what Will Streeter said. I feel the Dosco machine is further ahead than those in other areas.

Exxon - Will Streeter

The future plans of Exxon: 1) we will be back, 2) the question is when, 3) when the project is resurrected it will be different from what it is now. Exxon will go to belt haulage instead of trucks. Exxon will maintain some sort of engineering staff to look at these problems. We may not see 50,000 barrels/day at startup.

Sohio - William Hawes

Sohio is not scared. We have one project going and are most aggressive. As far as our own philosophy, we are looking seriously at mechanical mining.
We think if oil shale is going to be a viable source of energy, we must change our technology a lot. Mechanical mining can be a full fledged production mining tool and perhaps eliminate drill and blast. We will see a lot of changes. In fifteen months, Sohio has accomplished what its neighbors did in three years. We will be pursuing research projects to bring in mechanized mining.

**Phillips - Brad Cummings**

Phillips is pushing the White River project. We feel there is a good potential for mechanical mining. We tried a Dosco, it is a good machine and Dosco supports their machine. If we can get a machine that will cut hard rock, we will really have a system. Ventilation is definitely a problem. Tunnel boring machines can be used for primary openings.

**Occidental - Tom Watson**

Seven and eight retorts are progressing well. The production has not done much; so we are making plans for mothballing. We are doing trade-off study as to what degree of abandonment. We are doing lots of paper studies. Until you can prove something you have to start out small or lose a lot of money. We are looking at mechanical type miners. The trial at Logan Wash fell flat because we were cutting a low grade shale, a hard rock formation. We tried different types of bits, but we only cut 40 or 50 feet. Lots of dust was generated. (Comment Levent— for cutting oil shale, you have to penetrate deep.)

**COMMENTS**

**Robbins Company - Jim Friant**

There are five-six tunnel borers used in this country. They are permitted single entry with transformers ventilated. MSHA is sponsoring permissible transformers. In connecting mines, a separate escape way (have used 2' culvert) is required, allowing air to go across the transformer.
I will be happy to talk to anybody who will talk mechanical excavation and discuss what is new and what is coming.

Head Development, Inc. - Milton Head

We are looking at the possibility of using mechanical excavation in mining. We are going to see what we can put together.

Harrison Western - Larry Snyder

We are looking for someone that would want a machine and participate in development. I am a firm believer in mechanical excavation, and hope the oil shale industry will pick up.

EMI - Levent Ozdemir

From our viewpoint, we have presented our research under DOE with 6-8 months left at maximum. We would like to hear from you whether you feel such work should continue and if it does, who do you think should continue such work? Would oil companies be interested in further work and more research? Such work includes some laboratory initial feasibility testing, and the development of a program starting with a research phase, then going into prototype and field tests. Should such responsibility be with the manufacturer?

Exxon - Will Streeter

It has to be a sharing proposition. Maybe EMI could put together a package in which industrywide support would be feasible. EMI could contact all interested companies, get funding and put together a package which will satisfy everyone's needs. This might be a practical approach considering what is happening now. I suggest you request a donation from each company that you contact.

Phillips - Brad Cummings

We feel there is a potential for mechanical excavation. Its development should be the responsibility of the manufacturers. We want
a piece of equipment for production. Then we figure where we are and then assess our needs for technological research. We will not put money into it unless we know where the pieces fit. Until it is proven and fits into our scheme, we will not go along.

Exxon - Will Streeter

In regards to future research, Union is in a production mode. If you could get some project developed with manufacturers backing, use Union at Parachute and get to production scale. Utilizing material produced and being in production mode would reduce research costs.

Robbins Company - Jim Friant

One of the problems is that by and large the equipment manufacturers are not that big; resources are small. We are excavation specialists. There are better people than us that know how to handle the problems from there. The item that cuts the rock is an identifiable piece of the system. We don't want oil companies to sponsor you entirely. I want to know what kind of spacing and cutter geometry are optimum. Left to our own devices, we can only do a certain amount of research on our own. For some of our advanced techniques we see potential markets. How fast - is a matter of time. Industry must give more financial support for the development of mechanical excavation for oil shale mining. I would like to see a cooperative research program, some tests in both picks and discs.

GROUP DISCUSSION

Discussion followed questioning whether a number of manufacturers could work together. It was agreed there is a common need in knowing how to put that mechanical device on that piece of rock. Is there any particular test completed by EMI more important? If there is interest in looking at mechanical excavation, the place to start is EMI. Field tests are expensive. You will have to agree what you find in the field is supported
by our tests. In the laboratory there is more control over parameters.

We are asking you as potential users, do you think such a program should continue?

Mobil - A. H. Scrymgeour

We are in several industry research programs. A lot depends on the timing of a project. We feel industry must participate with manufacturers. We suggest that a firm written proposal be put together with finite money and go to the companies. Example - with one participating company, $X$ number of dollars is needed; with two participating companies, $X$ number of dollars is needed.

Mobil - Jim Lane

When accomplished, mechanical excavation is more than breaking rock; it is a whole system. Thought needs to be given to rock removal.

Sohio - William Hawes

We do not want a lot of crushing in the machine. We are looking for speed and production. You can buy crushers and put on behind.

EMI - Russell Miller

It is important to identify capabilities of mechanical excavation, and see how it ties in with current mining plans. Look at mechanical excavation, look at mining plans to take advantage of capabilities of the machine. If we put together a systems package, it could become unwieldy. We need first to test the capabilities of mechanical excavation.

Exxon - William Streeter

Won't you have most of the data you will need for a field test program?

EMI - Levent Ozdemir

The amount of tests to make firm conclusions would be available.
Following the conclusion of comments and discussion, a high speed movie of EMI's linear cutter was shown. Those persons interested were then given a tour of EMI's laboratories and equipment.

Note: Russell Miller suggested EMI send out the summary sheet developed for Phillips to those attending the conference to get a better idea of what is needed.

Participants are urged to fill in these forms and return to Dr. Ozdemir as soon as possible for a quantitative evaluation of everyone's needs. Results will be used in the establishing of the mechanical research program.