APPLICATION OF HEAVY DUTY ROADHEADERS FOR UNDERGROUND DEVELOPMENT OF THE YUCCA MOUNTAIN EXPLORATORY STUDY FACILITY

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ABSTRACT

Heavy duty roadheaders of 100 ton weight class are being considered for the excavation of the test rooms and alcoves along the main ramp and in the main repository level at the Yucca Mountain site. The current design of the candidate machines was studied and appropriate modifications are proposed. Computer programs for design optimization and performance prediction of roadheaders were developed. Results of computer modeling and operational parameters of the proposed machines are presented in this paper.

I. INTRODUCTION

The underground openings required by current plans for in situ tests at the Yucca Mountain Exploratory Study Facility (ESF) consist of various size and shape openings in different rock formations. These openings are mainly short drifts that can not be excavated by standard tunnel boring machines due to their length, different shapes, sizes, and angle to the main tunnels. Among current mechanical excavators, roadheaders are the only available machines to meet the requirements for excavating such openings due to their mobility and flexibility.

However, roadheaders are commonly used in soft to moderately hard and non-abrasive rocks. The challenge that they face at this job site is the welded tuff units that are in the range of 170 MPa (20,000 psi) unconfined compressive strength (UCS) and have a compact and quartz rich matrix. In order to use roadheaders in welded tuff, an extensive study of the design of bits and cutterhead was required. The machine must achieve deep penetrations to allow efficient cutting, high production and to prevent excessive bit wear. Deeper penetrations, however, create high forces on the head, which require high machine power and mass to react to these forces. Therefore, heavy duty hard rock machines with higher power and more mass have been considered for this project. This paper presents the results of a study performed at the Earth Mechanics Institute (EMI) of the Colorado School of Mines (CSM) on the application and performance prediction of heavy duty roadheaders for cutting the welded tuff units at Yucca Mountain.

II. BACKGROUND

The roadheaders are one of the most common and frequently used mechanical excavators. Their main advantages over other machines are their flexibility, ability to excavate various opening shapes and sizes, and access to the face. Traditionally, these machines have been used in soft to moderately hard rock and a magic number of 100 MPa (15,000 psi) UCS is considered as the upper limit of the rock strength that these machines can successfully attack. There are some cases where roadheaders were used in harder rocks, but only if they comprise a few percent of the total project. In general, the excessively higher bit cost and low production rates make the operation unfeasible in such rocks.

Following are solutions proposed for increasing the limit of the rock strength to be cut by these machines:

- change in material and design of the bits,
- improve the cutterhead design,

- improve the machine design to respond to the overall cutting head forces.

A. Cutter Design and Materials

The first item refers the restrictions that bit shape and mechanical properties impose on the forces applied to the rock by the bits. Obviously, for achieving deeper penetrations, higher cutting forces are required, and there is a limit to the maximum force and energy that could be transferred to the rock by the bits. Bit material must be abrasive resistant and ductile to withstand the impact loading while cutting in quartz rich rock types. Using tungsten carbide with cobalt alloys has partially solved the problem and improved bit life. Also, new brazing techniques and new methods to improve the abrasive resistance of the bit shanks have enhanced bit durability. In terms of bit shape, point attack (conical) bits, although they are not self sharpening as sometimes claimed, have increased bit life and efficiency due to their ability to maintain a certain profile over an extended period of time. Use of these bits has almost become standard on heavy-duty roadheaders.

In spite of major advances in bit manufacturing, yet point attack tools can not economically excavate hard and abrasive rocks. The application of disc cutters, which have been successfully used in hard rock boring, on roadheaders may provide the solution to hard rock cutting. So far, the large size of disc cutters has been the main factor preventing their application on roadheader cutting heads. Disc cutters, being the most common and the most efficient roller cutters, need significantly higher normal forces to penetrate into the rock than drag bits. Higher load means larger bearings and overall larger size discs, which physically can not be placed on roadheaders in any sensible pattern. In addition, machines could only maintain 2-3 cutters in contact with rock before becoming force limited (Since the load requirement of regular disc cutter is in the range of 10 to 20 tons). The limited number of cutters that could be placed on the head (or in contact with rock) basically means excessive vibrations, which are detrimental to cutting efficiency and machine life. Overall, the use of disc cutters on roadheaders has always raised the question of machine size and stiffness.

A minidisc cutter has recently been developed at the Colorado School of Mines Earth Mechanics Institute. The minidisc is 12.5 cm (5 in) in diameter, mounted on a 5 cm (2 in) shaft using a needle bearing. The bearing life of the minidisc is estimated at 100 hours with a load capacity of 7.5 tons (15,000 lbs) which is adequate for this type of application. The forces required to achieve a certain depth of cut with the minidisc are substantially lower than the regular disc cutters due to the smaller foot print area. The minidisc is light weight, very easy to handle and replace, and requires about the same space as the standard bit blocks on the roadheader cutterheads. With these unique characteristics, minidiscs are a highly promising solution for extending the application of roadheaders to excavation of harder rock formations.

B. Cutterhead Design

Between the two types of roadheader cutterheads, ripping (transverse) and milling (in line or axial) heads, the ripping type is more suitable for hard rock cutting. This is due to more efficient cutting during the sumping, resultant forces acting along the boom (and not perpendicular), better use of machine mass, and more efficient cleaning of the face. The spacing between the bits must be optimized by using the cutting test results. Also, cutter head layout must be balanced by controlling the placement of the cutters to create an even bit (force) distribution to minimize the vibration. This issue is of crucial importance since the increased spacing means less number of cutters and potentially higher vibrations. As mentioned before, the vibration of the head can have adverse effects on the production rate, machine life, and maintenance.

C. Machine Design

Machine design at this stage mainly refers to the machine mass and the ability to react to the cutting forces acting on the cutter head. Machine mass and overall geometry determines the magnitude and direction of the maximum forces that can be applied on the cutterhead. In essence, the force capacity of the machine (i.e. sumping, arcing, lowering, and lifting force) is a direct function of the machine mass. Higher machine masses are usually associated with the larger cutterhead sizes to provide for the reaction forces needed by such heads for the desired rate of production. One of the limiting factors has traditionally been the sumping force or the thrust capacity of the machine. This force is normally supplied by the tractive effort of the crawlers, which is generally inefficient, especially in soft and wet floors. Installation of telescopic booms on new generation of roadheaders has, to a large extent, solved this problem. Telescopic booms provide the sumping force while the machine remains stationary. This allows a better use of machine mass and friction between the crawler and the ground.

Arcing force capacity of roadheaders is another important restriction on production rate, especially for milling type heads, but also limits the production rate of transverse machines, given that enough torque and power is provided. A simple analysis of forces shows that increased arcing force can directly increase the force per bit as well as the penetration, and production rates. It must be noted that the main mode of production is arcing (or shearing), thus any increase in production of this mode increases overall production rate of the machine. Installation of a set of stelling jacks has been used as an effective means to increase the arcing force capacity of the roadheaders, but at the expense of machine flexibility.

Another parameter is the installed power and the gearbox assembly on the boom. While the axial head machines utilize direct gear reduction and compact transmission, transverse machines are somewhat limited in the size of gearbox and gear reduction. The high rotational speed and more loss of energy in the gearbox of the transverse machines have long been a drawback for this type of heads. High rotational speed means higher bit velocity and heat generated, thus reducing bit life. Sometimes, lower penetration resulting higher dust generation and over crushing of the material is attributed to higher rotational speed. For a given installed power, reducing the rotational speed means increase in available torque on the head to provide for deeper and more efficient penetration.

A combination of the above parameters has contributed to improved cutting ability of the road-headers.

III. CANDIDATE ROADHEADER FOR EXCAVATION IN WELDED TUFF

The current study followed up on the performance predictions made for different types of mechanical excavators for use at Yucca Mountain (Gertsch & Ozdemir 1991).[1] The previous studies have assessed the ability of different mechanical excavators for driving different shape and size openings in various rock formations. The studies were based on the data collected from linear cutting tests in samples of welded tuff with actual size cutters of various types.

One of the machine types considered in the studies was roadheader to excavate alcoves, cross cuts, and test rooms. These openings range in shape from rectangular to horse shoe, with various sizes and lengths. Obviously, among the mechanical excavation equipment, roadheader is the only machine which has the flexibility to meet the requirements for excavating such openings. But as previously stated, the current roadheader technology is limited in the hardness of rock which can be excavated economically.

A detailed and thorough study of midsize class roadheaders, their cutting head design and overall machine performance in welded tuff units present at the Yucca Mountain site were recently published.[2] Results of the studies to date show that most medium size roadheaders are incapable of cutting some of the welded tuff units. This class of machines, with a weight of about 50 tons and an installed cutterhead power ranging from 160 to 200 kW (200-270 hp), is neither heavy nor powerful enough to achieve reasonable excavation rates, as was discussed earlier.

Heavy duty machines can achieve a reasonable advance rate if some modifications are made to match the machine capabilities to the rock cutting characteristics. New roadheaders recently introduced to the market with higher power, mass, and other features such as telescopic booms, can be used for cutting welded tuff. These machines usually weigh about 100 tons with a cutterhead power up to 300 kW (400 hp). There are several suppliers for this class of roadheaders. Figure 1 is an example of a heavy-duty roadheader, an AM-105 made by Voest-Alpine with, transverse heads suited for hard rock tunneling. Technical data on these machines have been gathered and analyzed to evaluate their applicability and to incorporate possible modifications to the machine to achieve efficient cutting performance (Table 1).

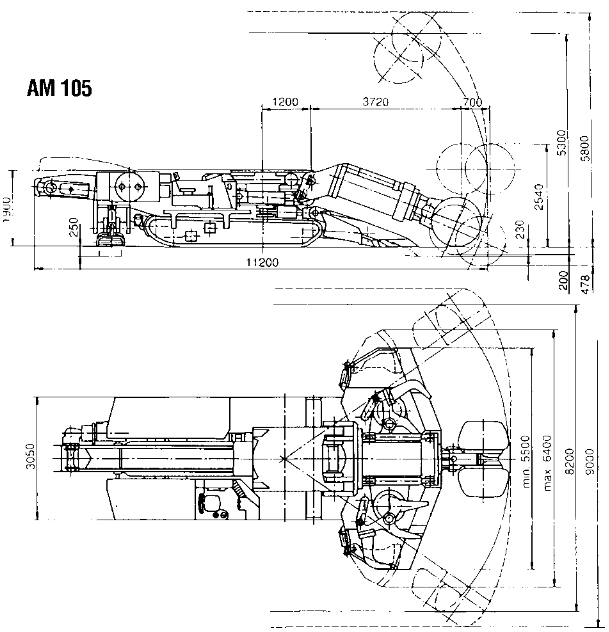

Figure 1. General Drawings of VA AM-105 roadheader

Table 1. General specifications of AM-105 roadheader.

Parameter	Value,	Unit	
Machine Weight	98	ton	
Cutting Speed	3.3	m/sec	
Lifting Force	150	kN	
(160 kN boom in telescopic pos. (15 and 16 ton))			
Arcing Force	100	"	(10 tons)
Lowering Force	300	"	(30 tons)
Sumping Force	700	"	(70 tons)
Slewing Speed	0.22/0.33	m/sec	
Cutterhead RPM	51	rev/min	
Cutterhead Power	300	kW	(400 hp)
Machine Length	11.2	m	(34 ft)
Machine Height	1.9	m	(6.5 ft)
Machine Width	3.05	m	(10 ft)
Loading Apron Width	5.5-6.4 m	(18-21 ft)	
Ground Pressure	0.13	MPa	(18.7 psi)
Loading and Conveyor HP	55	kW	(73 hp)
Hydraulic Power Pack	70	kW	(93 hp)
Conveyor Speed	0.8	m/min	(2.4 ft/min)
Tramming Speed	0-3.5	m/min	(0-10 ft/hr)
Negotiable gradients			
- Without Support	±20	gon	
- With Support	±30	gon	

The design and geometry of the cutterhead together with the operational parameters and performance of the AM-105 roadheader were analyzed and the results are presented in detail in a recently published report.[2] This machine can cut the welded tuff units, but with relatively low production rates and high bit costs. That is, they can excavate the required openings in welded tuff but not in a fashion which would be considered economical in a typical construction job. With the power and boom forces available to the cutting head, it is worthwhile to look for means to enhance the head design and cutting geometry and improve the efficiency and production rate of the machine.

This task was conducted by changing the cutting geometry through increased line spacing between the bits. The selected values of spacing were proven to be more effective as demonstrated during the previous cutting tests[1]. Spacing between the bits was increased to 36 mm (1.5 in) from 30 mm (1.2 in) and this simple change reduced the number of bits from 62 per head to 56 bits, a 10% reduction in the number of bits. Reduced number of bits means increased force and power available on each bit by the same proportion. For the selected line spacing, the normal force can be estimated by following equation as a function of penetration (see Fig 2):

$$F_n = A.\, p^b$$

Where Fn= Normal force (lbs)
P = Penetration (in)
A,b = coefficients equal to 4100 and 0.3 (for TSw-2), respectively.

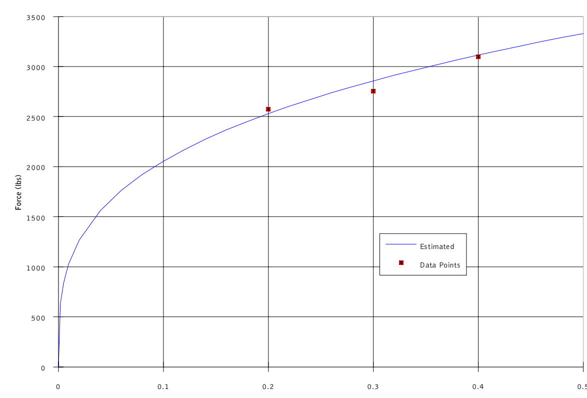

Figure 2. Estimated and measured normal forces.

This force estimation formula was derived by curve fitting the force data obtained from the linear cutting test of point attack cutters in welded tuff. The drag force can be estimated from the normal force using the drag coefficient, which is defined as the ratio of drag to normal force. Consequently, the force requirements for cutting at a certain depth of penetration were estimated, and used for cutter head balancing, as well as total force and power estimation. Using the spacing and general size of cutter head, designing the layout in cross section was possible by defining the position and tilt angle of the bits. At this stage, the number of bits required on the head, and general dimensions of cutter head (length and diameter) were specified. The next step was angular positioning of the bits to achieve an optimum bit distribution and minimize the head vibration. This was accomplished by a computer program developed for cutter head design and optimization of partial face machines.

IV. COMPUTER MODELING AND SIMULATION OF ROADHEADERS

A computer program was developed for bit allocation on the cutterhead as well as simulating the cutting process of the designed head.[2,5] This program has the capability to determine the position of the bits in 3D space with respect to the rock for different cutter head sizes and depth of sump. The program checks for rock-bit contacts and determines the number of cutters in contact with the rock at any given rotation angle of the head. Then, the actual penetration of each individual bit which is in contact with the rock is calculated and the force requirements for a given depth of penetration is estimated. The estimated forces are then projected on three mutually perpendicular axis (Cartesian coordinate system) established on the cutting head. The forces are added together to estimate the total force and moment requirements of the head in each mode of operation, namely the sumping and the arcing (slewing or shearing) modes. The cutting parameters calculated are then recorded for each position of the head as it rotates 360° with the desired angular increment. The result of this cutting process simulation can be plotted against the rotational angle and used for vibration analysis of the head (Fig. 3).

An algorithm for cutter allocation based on the concept of equal circumferential or angular spacing of bits[3] was used to achieve an even distribution of bits and forces on the head. This algorithm determines the angular position of the bits on the head to maintain a relatively constant number of bits in contact with rock as the head rotates. The angular positioning of the bits controls the bit distribution on the head once the number of bits are calculated from the selected spacing and number of starts. Figure 4. is an example of bit allocation map and Figure 5 shows

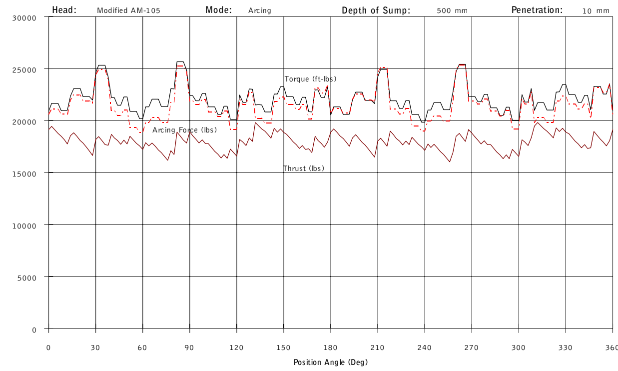

Figure 3. An example of vibration monitoring output, cutterhead thrust and torque variation.

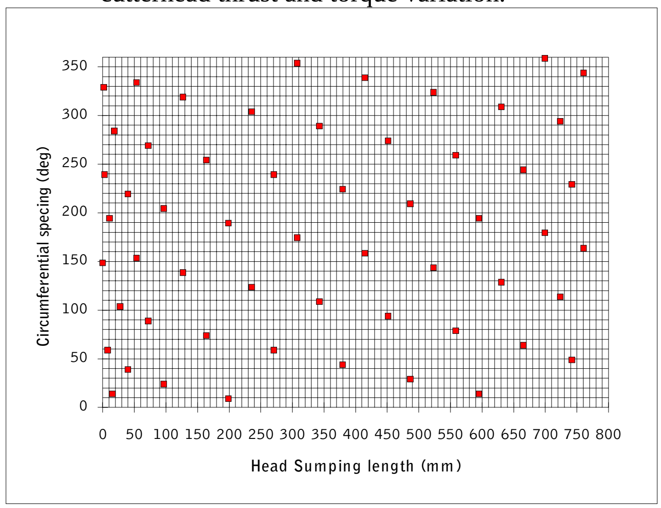

Figure 4. An Example of bit allocation map for 115°

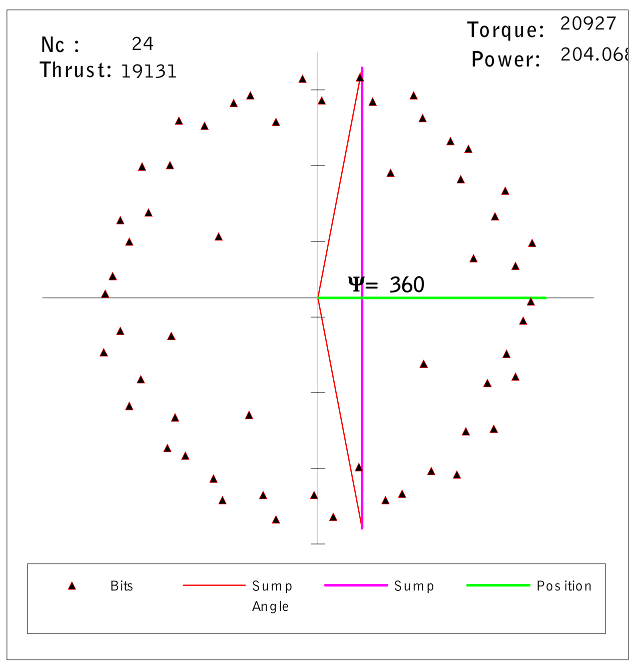

Figure 5. Plan view of the cutter head with 115° angular spacing.

the plan view of the same head. The combination of bit allocation algorithm and vibration simulation and monitoring in one program creates an ultimate optimization tool for cutting head design of partial face machine, especially roadheaders.

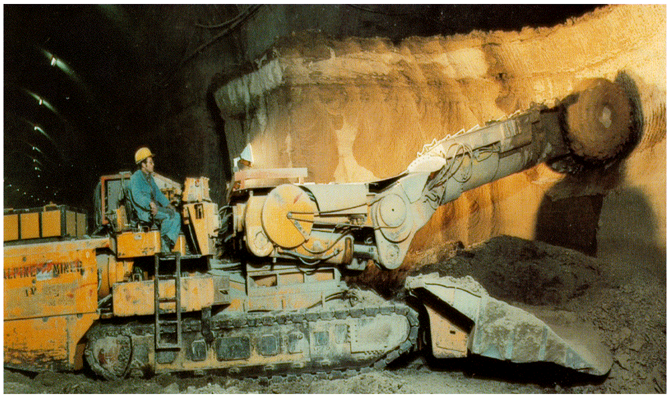

Figure 6. Drawings of the plan view and the cross section of the minidisc head of AM-105 roadheader.

V. MINIDISC CUTTER HEAD

A cutterhead featuring minidiscs was designed and optimized using the same procedure discussed above. The cutting forces for cutting a certain geometry with minidiscs in welded tuff formation were measured in extensive laboratory testing.[4] The coefficients "A" and "b" for force estimation was calculated at 15,500 and 0.3, respectively. The rolling coefficient can be estimated as follows:

$$RC = Tan(\frac{\phi}{2}) \text{ , } \phi = Cos^{-1}(\frac{R-p}{R}) \qquad (2)$$

Where: RC = Rolling Coefficient (F_r/F_n)
ϕ = Angle of contact area between disc-rock angular spacing.
R = Disc Radius
p = penetration

Knowing the normal force "F_n" and the rolling force "F_r", the cutter head force and power requirements were calculated. The cutter head design started with using a spacing of 50 mm (2 in) between the cutters and assuming a double-spiral single tracking design, as typically used on tunnel boring machines. The total number of discs needed was 24 using an optimum angular spacing of 140.5°. Figure 6 shows the drawings of minidisc cutter head in plan view and cross section. Despite the drastic reduction (70%) in number of cutters installed on the head, the vibration was minimized and maintained within a few percent of the original head design.

The results of calculations show that the cutter-head sumping force requirement is slightly higher due to higher thrust (normal force) required by discs, which is compensated by increased sumping force capacity of the telescopic boom. Arcing force requirement also increases for the same reason which is more difficult to counterbalance and may require the installation of stelling jacks. Meanwhile, the torque and power requirements are substantially reduced due to lower rolling force requirement of disc cutters. In other words, if enough forces are provided to the cutterhead, a substantially higher production rate can be achieved with the given installed power by using minidiscs. In fact, the main advantage would be the extended life of minidiscs and their capability to maintain their profile in hard abrasive rocks to sustain high production rates. Also, since the bit tip speed restriction does not apply to minidiscs, head rotational speed (RPM) can be increased, and this allows for a more efficient cutting regime with higher production rates and lower cutter costs. It is calculated that a machine featuring minidisc cutterhead with a mass of about 90 tons and head power of 400 hp can achieve a sump depth, 2-3 times greater than a similar machine laced with drag bits. The sumping depth for arcing of the minidisc head is twice that of a head with drag bits.

VI. PERFORMANCE PREDICTION

Performance estimates for the roadheaders laced with point attack bits as well as minidisc were carried out using four different methods. The first method used the specific energy values measured during the linear cutting tests. The second method was the estimating technique developed by Bilgin,[6] which utilizes UCS, RQD, and machine power to predict the performance of roadheaders. Third method was empirically developed by Neil[7] and further improved at CSM. This method utilizes the UCS, RQD, tensile strength of the rock along with head dimensions to generate production rate estimates. The fourth method is based on estimated forces and predicts the maximum production rates within the installed force and power capacities of the machine. A combination of these methods gives an envelope for the performance of a roadheader in a given rock type and the different methods can be compared to derive a more reliable estimate. The last three methods converge to the same point for RQD values over 90%. This confirms the validity of the methods despite the different bases used for their development. It must be noted that the first and fourth methods depend on the force measurements from laboratory cutting tests. Also, note that the rates quoted here are the "instantaneous production rates" (IPR) and must be adjusted for actual machine utilization. Table 2. contains the summerized result of performance prediction for all three machine designs.

Table 2. Performance prediction for AM-105 roadheaders

Original AM-105 Head Design								
Rock Formation	RQD	Selected/Recommended Production Rate			Advance Rt.		Bit Consumption	
	%	(m^3/hr)	((cyd/hr)	(ton/hr)	(m/hr)	(ft/hr)	(/m^3)	(/cyd)
TSw-2	35	16.36	21.36	36.65	1.09	3.84	1.72	1.32
	50	9.50	12.40	21.27	0.63	2.23	"	"
	65	5.80	7.60	13.00	0.40	1.37	"	"
	80	3.77	4.70	8.44	0.25	0.88	"	"
TCw	50	6.84	8.93	15.32	0.46	1.61	0.90	0.70
	70	5.80	7.50	13.00	0.40	1.35	"	"
	90	3.40	4.60	7.60	0.25	0.83	"	"
CH	90	55*	68.00	123.00	3.70	12.30	NA	NA
Modified AM-105 Head Design								
Rock Formation	RQD	Selected/Recommended Production Rate			Advance Rt.		Bit Consumption	
	%	(m^3/hr)	((cyd/hr)	(ton/hr)	(m/hr)	(ft/hr)	(/m^3)	(/cyd)
TSw-2	35	16.36	21.36	36.65	1.09	3.84	1.72	1.32
	50	9.50	12.40	21.27	0.63	2.23	"	"
	65	8.84	11.66	19.80	0.59	2.10	"	"
	80	5.25	6.78	11.76	0.35	1.22	"	"
TCw	50	7.50	9.26	16.80	0.50	1.64	0.90	0.70
	70	5.80	7.16	12.99	0.39	1.28	"	"
	90	4.94	6.10	11.07	0.33	1.08	"	"
CH	90	64.53	82.24	145	4.30	15.16	NA	NA
AM-105 Featuring Minidisc								
Rock Formation	RQD	Selected/Recommended Production Rate			Advance Rt.		Cutter Life	
	%	(m^3/hr)	((cyd/hr)	(ton/hr)	(m/hr)	(ft/hr)	(m^3/dics)	(cyd/disc)
TSw-2	35	NA						
	50	42.21	57.12	94.56	2.82	9.88	15.46	20.02
	65	25.77	35.01	57.79	1.79	6.07	9.50	12.30
	80	16.75	21.65	37.52	1.12	3.90	6.10	7.90
TCw	50	41.04	50.47	90.71	2.39	8.92	27.54	35.77
	70	34.80	42.39	76.97	2.08	7.48	23.10	29.99
	90	20.40	26.00	45.00	1.30	4.60	14.20	18.44

VII. CONCLUSIONS

The results of extensive laboratory testing and computer modeling show that the heavy-duty roadheaders equipped minidiscs can achieve substantially higher production rates with lower cutter costs than those utilizing drag bits. It is estimated that a heavy-duty roadheader, such as AM-105, can excavate the welded tuff units to be encountered in the construction of the Yucca Mountain Exploratory Study Facility at rates ranging from 40 to 100 ton/hr, depending on the degree of in-situ jointing and fracturing. Bit consumption estimates range from 6 to 30 m^3 per disc ring, again depending on RQD. Due to relatively low cost of minidisc cutters combined with their very high cutting efficiency the overall excavation costs should be highly favorable.

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