SAND91-7035
Unlimited Release
Printed September 1992

Distribution
Category UC-814

PERFORMANCE PREDICTIONS FOR MECHANICAL EXCAVATORS IN YUCCA MOUNTAIN TUFFS

SAND--91-7035

DE93 003232

by

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Under Sandia Contract 35-0039
Sandia Contract Monitor
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ABSTRACT

The performances of several mechanical excavators are predicted for use in the tuffs at Yucca Mountain: tunnel boring machines, the Mobile Miner, a roadheader, a blind shaft borer, a vertical wheel shaft boring machine, raise drills, and V-Moles. The work summarized here is comprised of three parts:

1. Initial prediction using existing rock physical property information.

2. Measurement of additional rock physical properties.

3. Revision of the initial predictions using the enhanced database.

The performance predictions are based on theoretical and empirical relationships between rock properties and the forces experienced by rock cutters and bits during excavation. Machine backup systems and excavation design aspects, such as curves and grades, are considered in determining excavator utilization factors. Instanteous penetration rate, advance rate, and cutter costs are the fundamental performance indicators.

Refinement of performance predictions using the new physical property data increases the tunnel boring machine advance rate 30 percent to 40 percent over the initial predictions. The cutter costs decrease by 12 percent to 15 percent.

The 25-foot (7.6-meter) diameter high-power tunnel boring machine achieves the highest predicted advance rate (162 feet/day or 49 meters/day). Shaft excavation is limited by the support systems to 40 feet/day (12 meters/day).

WORK BREAKDOWN STRUCTURE

The work discussed in this report was conducted under the aegis of Work Breakdown Structure (WBS) element 1.2.4.2.1.3, entitled "Rock Mechanics Field Testing."

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ACKNOWLEDGMENTS

This report represents the combined efforts of a number of people from both Sandia National Laboratories (SNL) and the Colorado School of Mines (CSM). Special thanks are extended to Dr. Frank Hansen of SNL who served as the SNL principal investigator, and to CSM students J. Rostami, B. Asbury, and S. Daniels who performed the majority of the laboratory test work.

1.0 INTRODUCTION

The work described here was performed for Sandia National Laboratories (SNL) as part of the Yucca Mountain Site Characterization Project (YMP). The project is part of the U.S. Department of Energy's (DOE) program to safely dispose of high-level radioactive waste from nuclear power plants.

The DOE has determined that the safest and most feasible method currently known to dispose of such wastes is to place them in a mined geologic repository. The YMP is conducting detailed studies to determine the suitability of siting a potential repository at depth in the welded tuffs of Yucca Mountain, Nevada. The rock mass will be characterized by excavation of an Exploratory Studies Facility (ESF) prior to potential repository construction. Various means of excavating the ESF and the repository are being examined, including mechanical excavators.

Preliminary feasibility studies are standard procedure in the mechanical excavation industry. Such studies determine if a project is technically and economically feasible, and if so, they indicate the expected performance of the excavator using the best data already available. Preliminary feasibility studies provide the initial performance estimates for the construction engineer. These performance estimates must be refined (usually in several stages) as more data become available.

1.1 Scope

The primary purpose of the work reported here is to provide preliminary estimates of how selected mechanical excavators would be expected to perform in the welded tuffs that will be encountered during construction at the ESF site. The estimates provided here will assist preliminary scheduling, planning, and costing for ESF construction.

The scope of work for this study was divided into the following subtasks:

- Excavator performance prediction using existing data -- Performance estimates were developed for the various types of mechanical excavators in Yucca Mountain tuffs using existing physical property data obtained from the Reference Information Base (RIB), Version 4 (Appendix C).

- Additional physical property tests -- A series of additional physical property tests were conducted to obtain those rock properties that are known to influence the mechanical boreability of rock.

- Revised performance predictions -- The newly acquired physical property data were used to refine the preliminary performance estimates developed in the first subtask.

1.2 Excavation Systems Considered

The ESF will consist of combinations of shafts, raises, drifts, ramps, alcoves, and chambers or rooms. To construct these diverse openings, several types of mechanical excavation systems are evaluated in this study:

tunnel boring machines (TBMs), the Robbins Mobile Miner, roadheaders, the blind shaft borer (BSB), the vertical wheel shaft boring machine (SBM), raise borers, and the V-Mole.

The TBM is best suited for relatively long, straight openings. Figure 1-1 is a simplified schematic drawing of a TBM showing its basic components. The TBM is a high production machine that has been proven effective in a wide variety of rock types and ground conditions. TBM technology has advanced to the stage where nearly any type of rock can be bored, provided the machine is properly designed for the conditions to be encountered. Under favorable conditions, TBMs are capable of spectacular advance rates at costs much below those of drill-and-blast techniques. Recent improvements in TBM technology include larger and more efficient cutters which can be back-loaded, enhanced steering control, more effective roof and ground control systems, and significantly improved machine reliability. Conveyor muck haulage is replacing the traditional rail transport systems, offering truly continuous muck haulage. Especially in softer rocks, conveyor haulage removes the limitation on TBM advance often caused by rail haulage volume limitations. New TBM designs have also been developed for making turns much tighter than were previously feasible. The TBM is most suitable for excavating ramps and long drifts where high production rates can be achieved.

The Mobile Miner (Figure 1-2), a relatively new machine design, provides the capability to excavate rectangular openings in rocks ranging from soft to hard. It is the only mobile machine currently available to excavate rectangular openings in hard rock. It is less suitable than a TBM for large openings, either in length or cross section, because it is not a full-face machine and cannot match TBM production rates. For ESF construction, the Mobile Miner appears to be most suitable for excavating side rooms off of the main tunnels excavated by the TBM. It can also be used to drive shorter drifts or crosscuts or any other openings for which a rectangular cross section is desired. Design efforts also are under way for a Mobile Miner with a ranging cutterwheel to allow the excavation of horseshoe-shaped openings.

The roadheader (Figure 1-3) is a highly versatile mobile excavator with the capability to excavate openings of various shapes and sizes. It is a very common machine in mining and underground construction, although its use is limited to low- to medium-strength rock, usually less than 12,000 psi (83 MPa) compressive strength. Higher strength rocks can be excavated successfully if the rock is extensively jointed. This machine's mobility allows easy relocation from site to site; also, it can achieve high production rates in soft, nonabrasive materials. For ESF exploration and construction, the roadheader can be used to excavate crosscuts, short ramps, and drifts, as well as small side rooms off of the main drifts excavated by the TBM. It also is useful for finishing the shaping of complex openings.

The design and operation of the BSB closely resemble a double-shielded TBM (Figure 1-4). The cutterhead design is modified to allow muck pickup from the shaft bottom. The current BSB design collects muck with a pair of chain conveyors and transfers it to a central bucket elevator. The muck is then transported to the surface with a standard shaft skip hoisting

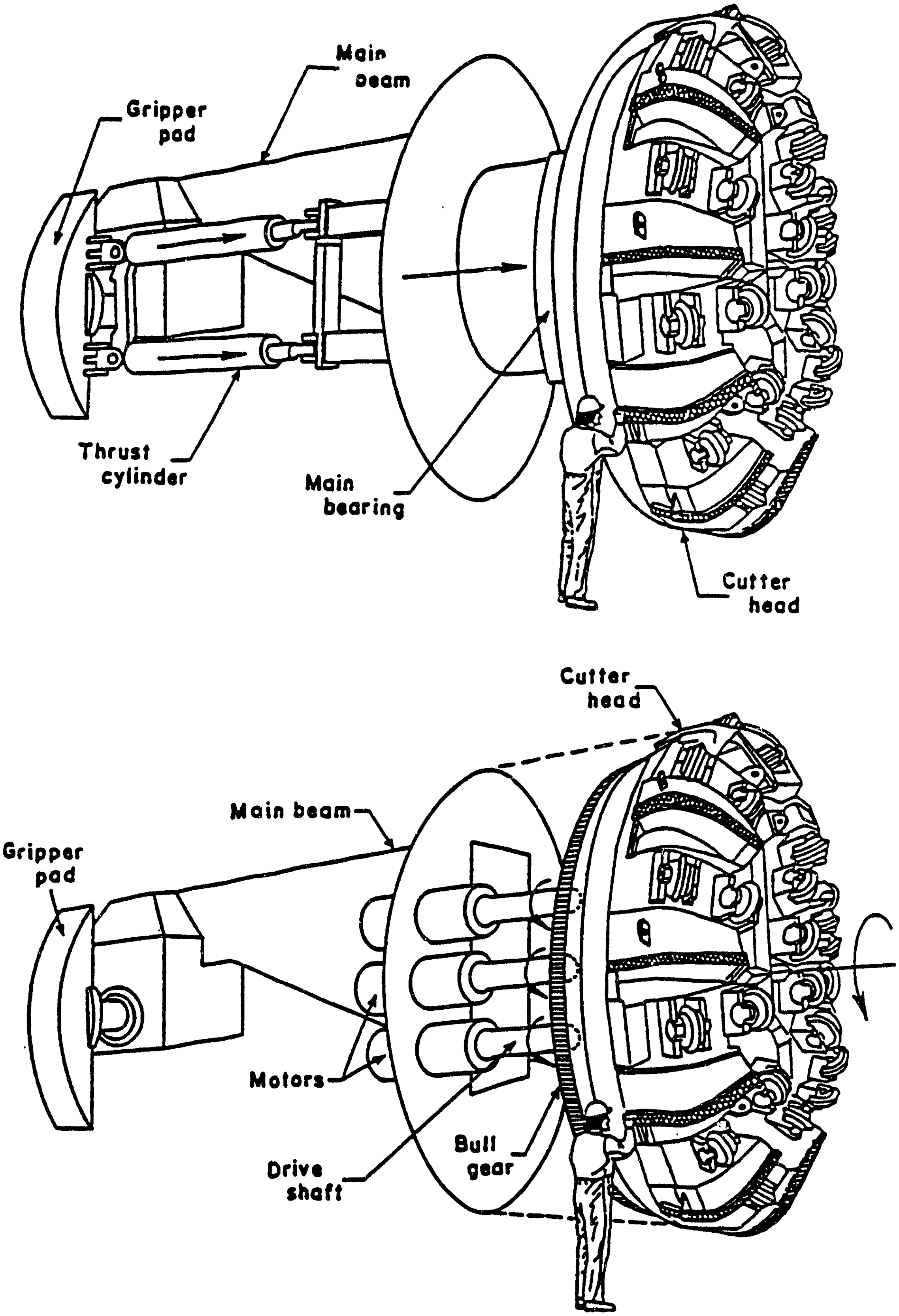

Figure 1-1. Schematic Drawing of Generic Thrust and Torque Systems of a Tunnel Boring Machine (TBM), Courtesy of The Robbins Co.

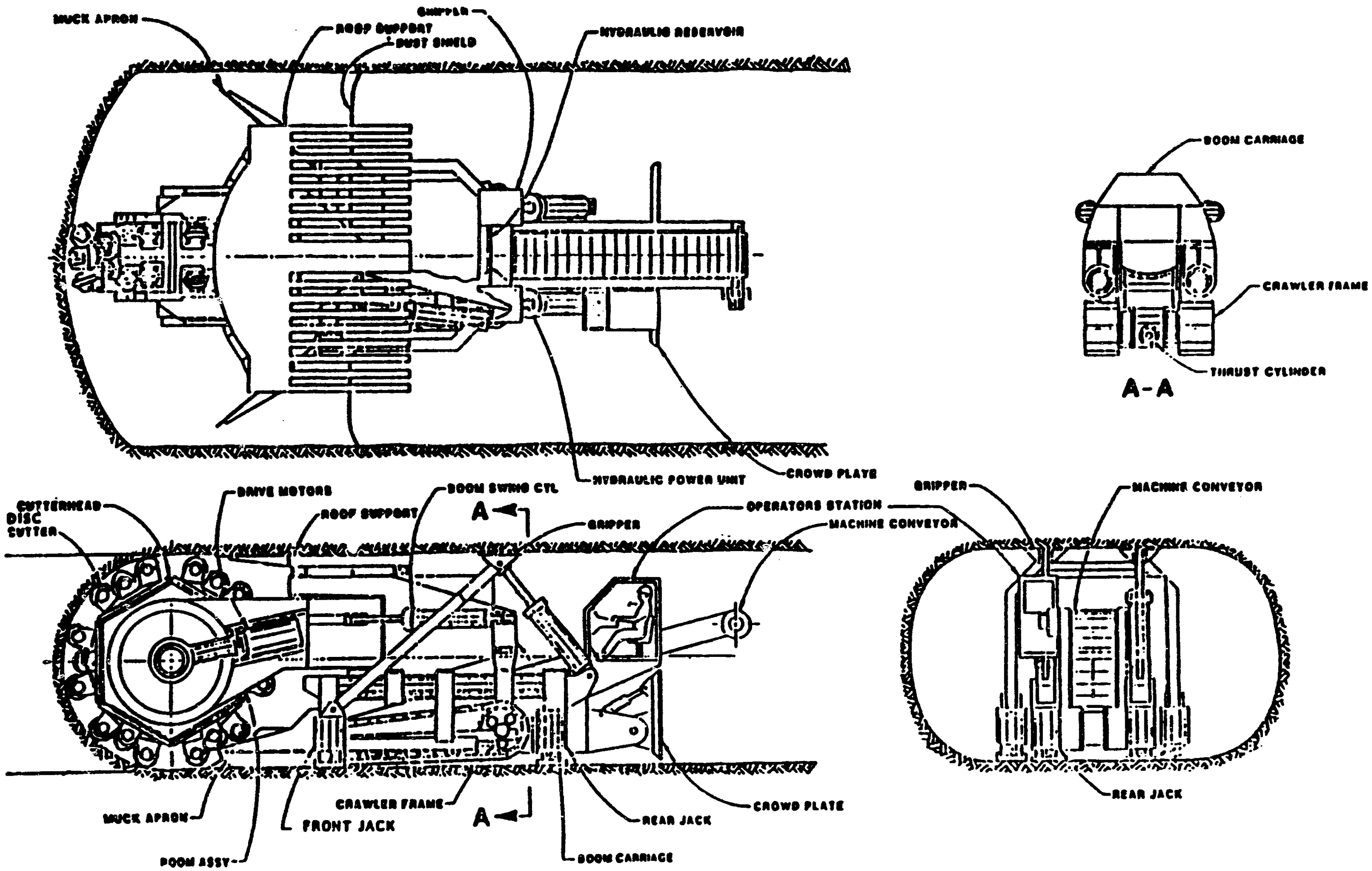

Figure 1-2. Schematic Views of the Mobile Miner in Operation, Courtesy of The Robbins Co.

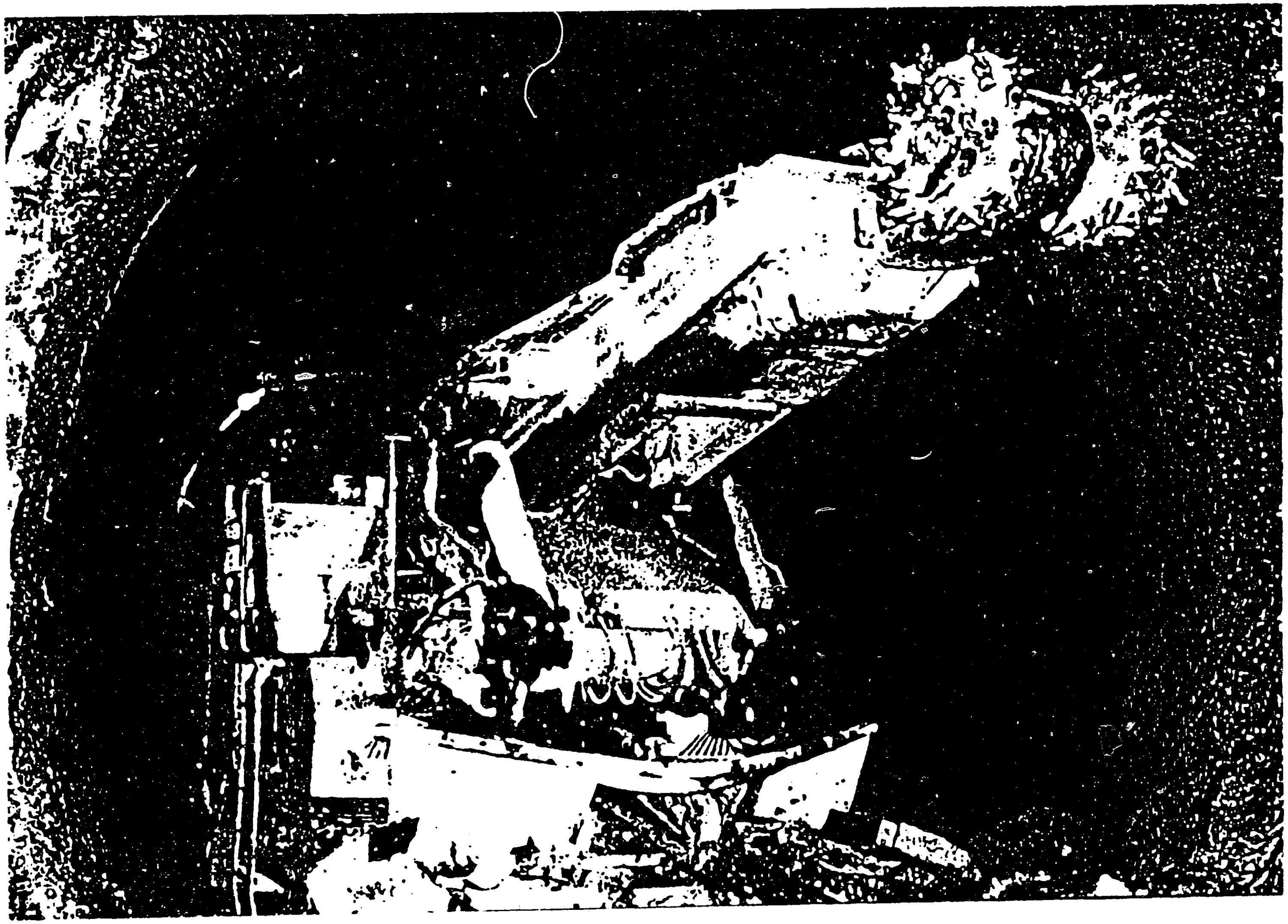

Figure 1-3. A Ripper-Type Roadheader, Courtesy of Voest-Alpine GmbH

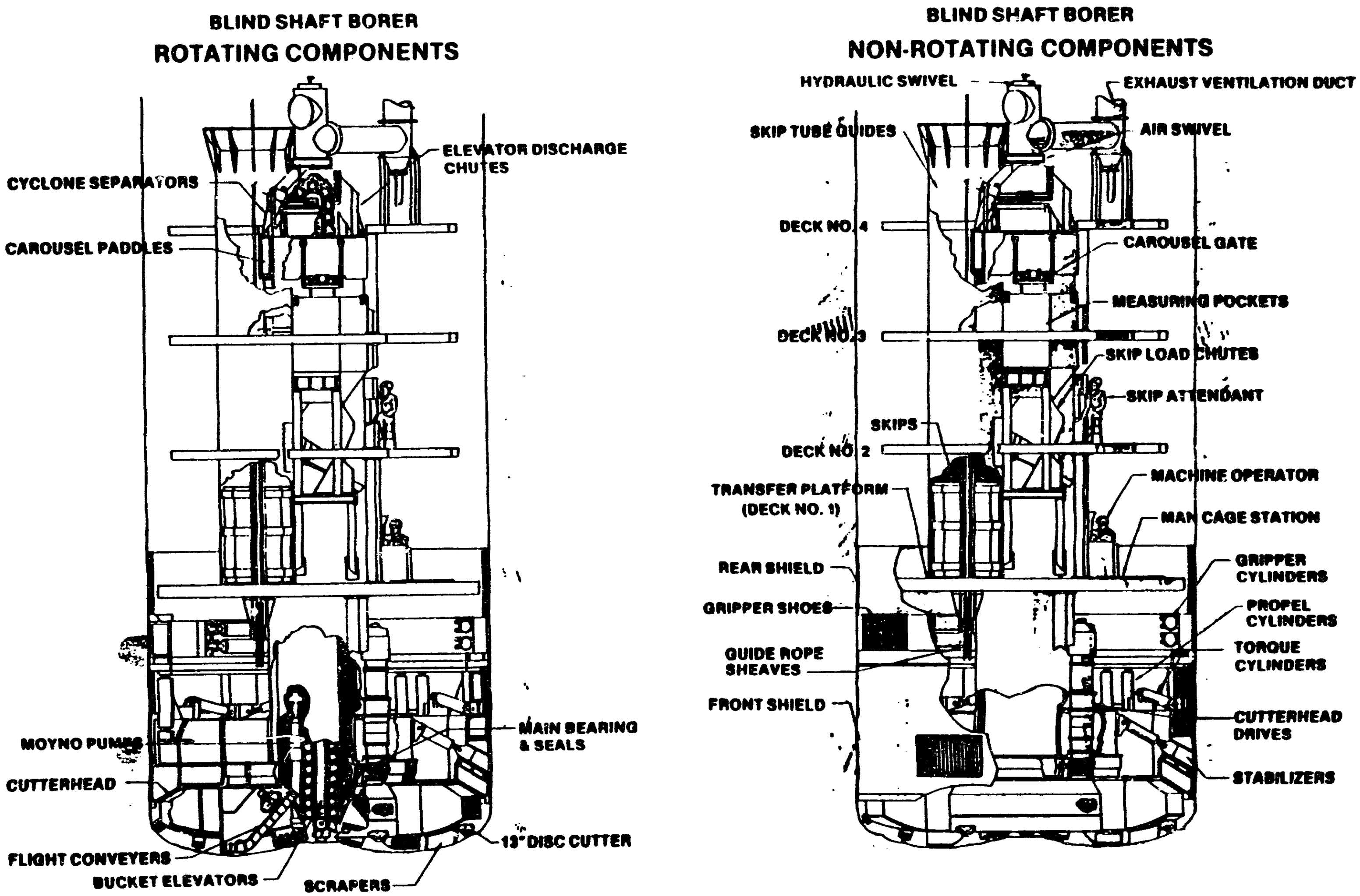

Figure 1-4. Schematic Drawing of the Components of a Blind Shaft Borer (BSB), Courtesy of The Robbins Co.

system. Thus, the BSB is a dry shaft boring device, using a mechanical muck pickup system rather than water flushing. As with other mechanical shaft excavation systems, its performance is governed primarily by the limitations of the muck removal and the shaft lining systems.

The SBM is an adaptation of the Mobile Miner for vertical downward excavation (Figure 1-5). It is a relatively new concept for the mechanical excavation of shafts in rock. The rock is excavated by a rotating, thin cutterwheel equipped with a series of peripherally mounted disk roller cutters. The cutterwheel assembly rotates about the shaft axis, while being thrust downward, in addition to the cutterwheel rotating about its own horizontal axis. A bulldozer-type blade follows the cutterwheel and scrapes the cuttings into a pile. A clamshell bucket picks up the pile at intervals and loads it into a hoist for transport to the surface. A new design version of the SBM features a cutting wheel of the same diameter as the shaft to be bored. It is believed that the new design will allow greater cutter loads for higher excavation rates.

Raise boring (Figure 1-6) is a relatively fast and highly efficient technique for construction of raises and small shafts. Raise boring uses a pilot hole and therefore requires underground access for operation, including muck removal. Access to the face for science investigations during excavation can present serious safety hazards, particularly in fractured or blocky ground. The bit must be completely withdrawn from the bore for personnel to reach the face. Raise boring is the most widely used method of raise construction, but with current technology it is limited to 20-ft (6.1-m) diameter raises. The maximum raise depth is ~3000 ft (914 m). This is controlled primarily by hole deviation considerations.

The V-Mole (Figure 1-7) is a mechanical shaft reamer. It reams a previously drilled pilot hole downward to the final shaft diameter. The pilot hole, which usually is created by a raise borer, serves as a passage for removal of the rock cuttings generated during the reaming operation. Because of the need for a pilot hole, the V-Mole requires existing underground access, meaning it cannot be used to excavate blind shafts. Numerous mine shafts have already been constructed with V-Moles. Overall, the V-Mole has achieved advance rates much higher than those feasible with conventional drill-and-blast shaft excavation. Shaft lining can be installed directly above the machine as it reams downward. Pilot hole deviation can be compensated by steering corrections of the reamer itself. In recent years, a blind version of the V-Mole using a hydraulic muck pickup system has been developed and field-tested in various coal mines in Germany. Its performance has been encouraging, although the hydraulic transport system suffered severe wear on several important components. This resulted in very low machine utilization. Work is currently under way to improve the efficiency and reliability of this advanced system.

More detailed descriptions of the excavators used in this study are included in Appendix A.

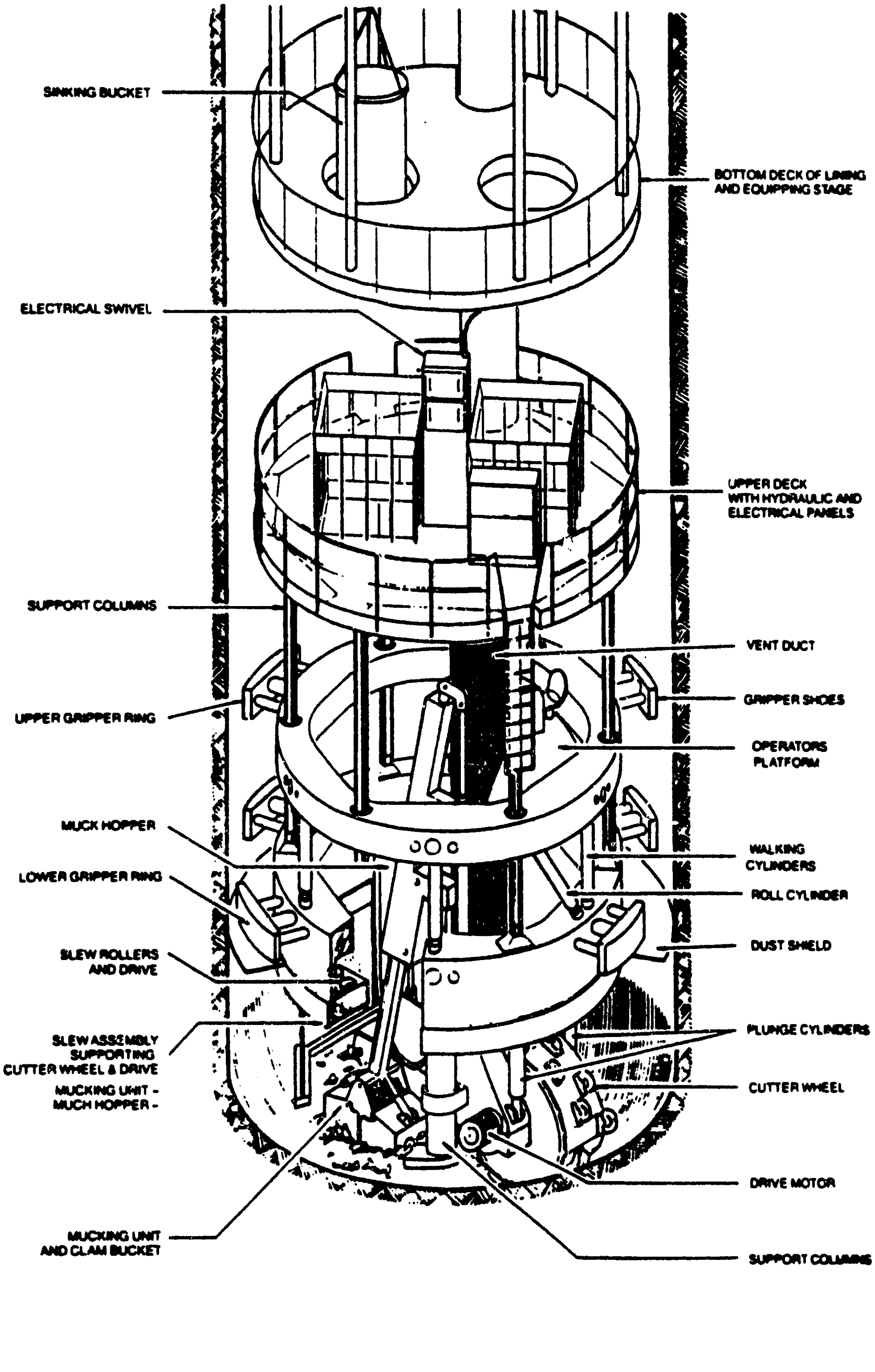

Figure 1-5. Schematic Drawing of a Vertical Wheel Shaft Boring Machine (SBM), Courtesy of The Robbins Co.

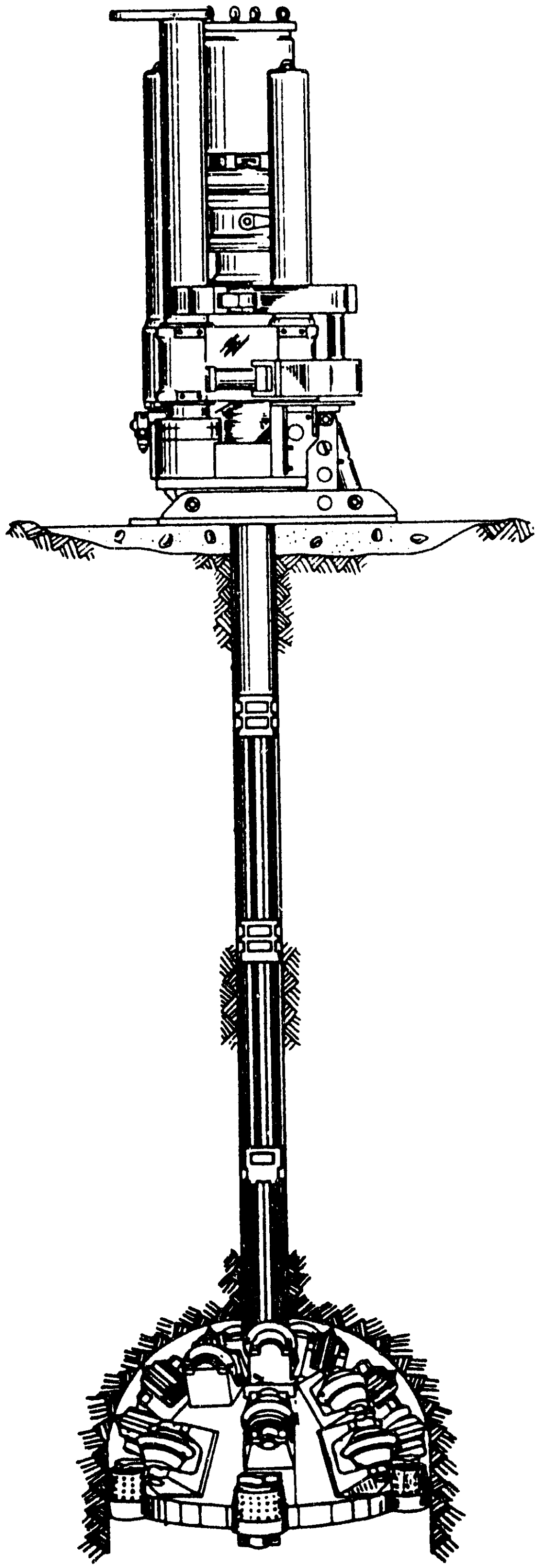

Figure 1-6. Schematic Drawing of a Raise Drill With a Domed Reamer Head, Courtesy of The Robbins Co.

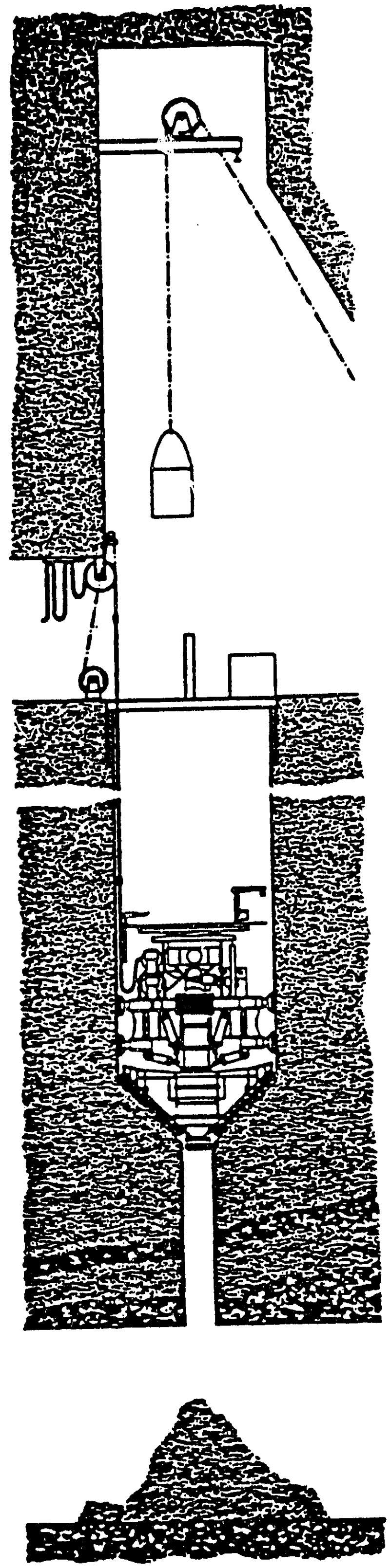

Figure 1-7. Schematic Drawing of a V-Mole in Operation, Courtesy of Wirth GmbH

1.3 Excavation Requirements

Although the final design for the ESF at Yucca Mountain has not been initiated, several conceptual design descriptions in the Site Characterization Plan Conceptual Design Report (SCP CDR) (SNL, 1987) and in the ongoing DOE ESF Alternatives Study provided the basic excavation parameters for the performance predictions developed in this task. The necessary parameters of each opening included diameter or size, length of drift or depth of shaft, and slope or attitude. Using this information, opening dimensions were assigned and specific machines were selected.

1. Tunnels (drifts) of various cross-sectional areas and shapes.

   a. A tunnel boring machine for circular drifts 25 ft (7.6 m) in diameter -- Two machines, one a standard configuration and the other a high-power configuration, were evaluated. Both were hard rock, open-gripper-type TBMs. The standard machine was equipped with 17-in. (43-cm) diameter disk cutters, each rated at 50,000 lbf (0.222 MN) average load. The high-power TBM used the newly developed 19-in. (48-cm) diameter disk cutters with load ratings of 65,000 lbf (0.289 MN). In addition, the high-power TBM rotates at 7.0 rpm rather than the standard configuration.

   b. A Mobile Miner for rectangular drifts 14 ft by 22 ft (4.3 m by 6.7 m) and 16 ft by 30.5 ft (4.9 m by 9.3 m).

   c. A roadheader for horseshoe-shaped drifts 22 ft wide by 12.5 ft high (6.7 m by 3.8 m) and 15 ft wide by 21.5 ft high (4.6 m by 6.6 m) -- A heavy-duty machine was selected.

2. Vertical shafts of 16-ft (4.9-m) diameter (after application of 1-ft or 0.3-m lining).

   a. A shaft boring machine, 18-ft (4.9-m) diameter, vertical wheel, partial-face type.

   b. A blind shaft borer, 18-ft (4.9-m) diameter, full-face type -- Performance was calculated for two speeds of operation. The penetration rate for both machines was fixed at 6.0 ft/hr (1.8 m/hr) to account for the limitations imposed by hoisting and lining considerations.

   c. A raise drill, 18-ft (4.9-m) diameter -- A Robbins model 103 RM-DC raise drill was assumed. The 18-ft (4.9-m) diameter reamer head would be a custom design, fitted with 26 disk cutters of the 4-row, tungsten-carbide insert type. The cutters would be spaced 2.0 in. (5.1 cm) apart.

   d. A raise drill, 6-ft (1.8-m) diameter, to drill a pilot hole for the V-Mole -- This is a standard size, available off the shelf (a Robbins model RR6E). The reamer mounts 10 cutters, each containing four 15.5-in. (39-cm) diameter disk cutters set with tungsten-carbide inserts.

e. A V-Mole, 18-ft (4.9-m) diameter, shaft reamer -- A currently available model and an upgraded version were evaluated.

1.4 Prediction Methodology

Performance prediction methods for mechanical excavators are founded on basic principles, empirical methods, and professional engineering judgment. The state of the art has not advanced to the point where predictions based on rock properties can rigorously follow from basic considerations. The problem stems from the variability and complexity of the rock response to mechanical cutting. Rock properties vary spatially to the extent that significant differences in cutability can occur in a single excavation. The response of the rock to mechanical cutting action is very complex, especially when internal weaknesses are present in the form of joints, bedding, or foliation. Rock elasticity, texture, grain size, shape, bonding, and the nature of the matrix material also have significant impact on the performance of mechanical excavators.

The prediction methodology usually focuses on the action of an individual cutter on the rock and then is generalized to the action of the entire machine and its backup system. The prediction techniques can also be used for conducting performance optimization studies to determine the most efficient cutterhead design and cutter layout to achieve the highest advance rate based on muck removal and excavation support requirements.

Extensive studies of cutter-rock interactions have led to the development of empirical and theoretical relationships between certain rock properties and cutter performance. Depending on cutter type (pick or disk), the prediction methodology uses rock-compressive, shear, or tensile strengths together with other information related to rock brittleness, texture, foliation, bedding, and the presence of joints and microfractures.

The performance of a mechanical excavator is best described by the achievable instantaneous rate of penetration, the utilization percentage (which leads to advance rate), and the cutter costs. Normally, estimates of these parameters would then be used as input for estimating the overall project schedule and costs.

The penetration rate is the distance the machine actually bores into the rock per unit time of operation. Penetration rate is expressed in units of feet per hour (ft/hr) and is controlled by the design and power output of the machine, as well as the characteristics of the rock being excavated.

The utilization determines the actual forward advance the excavator achieves. The rate of advance is the length of excavation created per unit of elapsed time, usually expressed as feet per 24-hour day (ft/day). Multiplying the penetration rate by an estimate of machine utilization gives the advance rate. Utilization is the fraction of elapsed time during which the machine actually is excavating rock. As might be expected, utilizations depend on a multitude of factors and can vary widely from project to project, even from location to location within a project. Utilization is a function of the entire excavation process, particularly opening design parameters such as curves and grades, and machine parameters such as the backup system. It also includes rock mechanics aspects, scheduling, personnel training, and any activities that interfere with the boring operation, such as geologic mapping and science experiments. In general, machine utilization is low in the early phases of a project. As personnel become more familiar with the machine and the rock conditions, the utilization factor usually improves, generally reaching its highest value in later phases of the project.

Cutter costs are the material costs of replacing cutters as they wear out during the excavation process. These costs usually are expressed in terms of dollars per cubic yard of material excavated. In very hard, abrasive rock, cutter costs can significantly impact the economic feasibility of machine excavation compared to drill-and-blast excavation.

Because the ESF construction environment will be unique, instantaneous penetration rates (ft/hr) are reported here along with the advance rates (ft/day). The advance rates are based on machine utilization factors currently experienced with state-of-the-art mechanical excavation systems in civil underground construction. Machine utilization factors for a project such as the ESF may be significantly different from the utilization factors used in current mining and construction projects.

The manners in which the rock properties are applied to machine performance prediction depend on the machine being considered. Different machines use different types of cutters, in different arrangements, and on different frames. Appendix A discusses the specific performance prediction procedures used for the types of excavators included in this study.

2.0 PRELIMINARY PERFORMANCE PREDICTIONS

2.1 Introduction

The first step in any prediction of excavator performance is to perform a preliminary study utilizing the data at hand. The available appropriate rock properties were extracted from the Reference Information Base (RIB), Version 4. The RIB provides data that are in common use by Yucca Mountain Site Characterization Project (YMP) participants. The minimum rock properties needed for input into the predictive model are uniaxial compressive strength (UCS), tensile strength, abrasivity, and rock quality designation (RQD). The use of these model input values in performance prediction is discussed in Appendix A. Table 2-1 lists the range of uniaxial compressive strengths used in the preliminary study. Tensile strength and abrasivity were not directly available from the RIB, Version 4, and were estimated using professional engineering judgment. RQD values (ranging from 50 percent to 75 percent) were extracted from Langkopf and Gnirk (1986).

Table 2-1

Uniaxial Compressive Strengths Used for Initial Performance Evaluation[1]

Thermomechanical Unit	Compressive Strength (psi/MPa)
TSw1 (LR - lithophysae rich)	2,350/16
TSw1 (GU-3 - lithophysae poor, well USW GU-3)	10,000/69
TSw1 (G-2 - lithophysae poor, well USW G-2)	25,380/175
TSw2	22,480/155
TSw3 (G-2 - well USW G-2)	7,540/52
TSw3 (G-4 - well USW G-4)	10,880/75
CHn1v	13,050/90
Chn1z	3,770/26

[1]From RIB, Version 4. TS - Topopah Spring, TSw[1] - Upper Topapah Spring Member, TSw[2] - Middle Topapah Spring Member, TSw[3] - Lower Topapah Spring Member, CH - Calico Hills, w - welded, n - nonwelded, v - vitric, and z - zeolitized.

2.2 Results

The performance predictions for the various types of mechanical excavators based on previously existing data are given in Appendix A together with detailed discussions of the equipment considered, the prediction methodology used, and factors which affect the utilization, including the backup system, muck removal, ground support, excavation slopes and curves, water inflow, rock quality, crew training and motivation, and science access. These results form the basis for the comparisons discussed in Section 4.2.

3.0 PHYSICAL PROPERTY MEASUREMENTS

3.1 Introduction

The initial performance predictions were calculated on the basis of physical property data available in Version 4 of the RIB and SAND reports. The physical properties summarized in this section form a basis for refining those performance predictions by providing additional pertinent physical properties.

The purpose of this section is to present the additional physical property measurements which were conducted to expand the existing information that is useful for excavator performance prediction. The work discussed here is not intended to characterize or extend the database of potential repository rock types, but only to refine the preliminary performance estimates for the types of mechanical excavators considered in this study.

The physical property data for the first stage of refinement of the performance predictions were obtained from the following series of tests:

- Thin-section petrographic analysis--Basic knowledge of mineralogic and microstructural characteristics allows accurate prediction of the wear to be expected on cutters.

- Physical properties tests--A suite of physical properties tests known to be relevant to the mechanical boreability of rock was performed to provide data for mechanical excavator performance prediction:

  - Bulk density--Density primarily affects the muck-handling requirements of the excavator.

  - Uniaxial compressive strength (UCS)--The compressive strength is one of several important parameters affecting rock excavatibility; however, the degree of its importance depends on many other factors.

  - Splitting tensile strength (Brazilian test)--The tensile strength indicates the toughness of the rock fabric and its resistance to fracture initiation and propagation during cutting.

  - Ultrasonic pulse velocities and dynamic elastic constants--Acoustic velocities, dynamic Young's modulus, and dynamic Poisson's ratio indicate the competency of the rock and its brittleness, which strongly affect its ease of excavation.

  - Cerchar abrasivity index (CAI)--This indirect abrasion test gives a reliable indication of the rock abrasivity and the bit wear to be expected.

- Estimated abrasivity--The quartz content of the rock provides a rough measure of its abrasiveness.

- Compressive-to-tensile-strength ratio--This is an aggregate measure of the toughness of the rock fabric.

- Point load strength--The force-penetration behavior indicates the forces required to cause the rock to fail.

- Punch penetration behavior--This test uses indenters manufactured from excavator cutters for a more accurate determination of required cutter loads and penetrations. It also provides a good indication of rock elasticity and energy-absorbing characteristics.

The tests described above were conducted on rock samples from Busted Butte, Fran Ridge, and the G-Tunnel. The samples from Busted Butte and Fran Ridge were taken from outcrops of the TSw2 thermomechanical unit of the Topopah Spring Member of the Paintbrush Tuff (Ortiz et al., 1985). This unit is being proposed for construction of a potential repository. Samples from the G-Tunnel represent the Grouse Canyon Member of the Belted Range Tuffs at Rainier Mesa.

3.2 Thin-Section Petrographic Analysis

Qualitative petrographic examination of thin-sections from all three locations show that all are moderately to highly welded and are devitrified. Some samples show the effects of several stages of recrystallization. Samples from the G-Tunnel exhibit fewer microfractures than did the TSw2 samples. Tuff samples from all three locations are fresh and unweathered throughout. A section of Appendix B contains supplementary photomicrographs and a summary table of the findings from individual thin-sections.

3.3 Physical Properties

Table 3-1 summarizes the density, UCS, splitting tensile strength, ultrasonic pulse velocities, dynamic elastic constants (Young's modulus and Poisson's ratio), CAI, point load strength, and punch strengths of samples of the tuffs. Appendix VI of Appendix B contains more detailed descriptions of the procedures followed for each test, in addition to presenting the results in the form of plots showing average values and their 95 percent confidence limits.

Table 3-1

Average Physical Property Values Measured for This Study

Sample Origin	Density (lb/ft^3)	P-Wave Velocity (ft/sec)	S-Wave Velocity (ft/sec)	Dynamic Young's Modulus (10^6 psi)	Dynamic Poisson's Ratio
Fran Ridge	144.9	14700	9436	6.33	0.14
Busted Butte	144.0	14740	9981	6.65	0.07
G-Tunnel	143.1	13790	8705	5.46	0.17

Sample Origin	Cerchar Abrasivity Index	Tensile Strength (psi)	Compresive Strength (psi)	Compressive-to-Tensile Ratio	# Tests Per Value
Fran Ridge	4.39	2156	15040	7.0	21
Busted Butte	4.48	2486	20620	8.3	6
G-Tunnel	4.36	1486	15680	10.6	9

4.0 REVISED PERFORMANCE PREDICTIONS

4.1 Introduction

Based on the results of the additional physical property tests, particularly the abrasivity and punch-penetration measurements, the preliminary performance estimates were revised for all the mechanical excavators evaluated in this study. Overall, the new data revealed the following important information regarding the mechanical boreability of the Yucca Mountain welded tuffs.

For the preliminary performance predictions, tensile strength was estimated on the basis of data from similar rock types. The additional physical property tests showed that the tensile strength is lower than estimated in this way. Tensile strength reliably indicates rock resistance to failure due to the fracturing and chipping action of the cutters. Thus, lower tensile strength means that less energy is consumed in chip formation, leading in turn to reduced energy required for excavation.

The brittleness of rock critically influences its mechanical excavatibility. In general, increased brittleness enhances cutability by allowing more effective chipping and faster crack propagation between adjacent cutter paths. Also, in brittle rocks the cutters can be spaced farther apart, resulting in the production of bigger chips. This directly reduces the specific energy required for cutting and raises productivity. Cutter costs also are reduced per unit volume of material excavated.

Punch-penetration tests provide accurate indications of the brittleness displayed by rock in response to penetration by a mechanical tool. Higher brittleness causes more violent chipping during punch penetration. The force-penetration curves of brittle rock drop off suddenly as each chip forms, in response to the force relief. The force-penetration curves for the welded tuff samples that were tested showed a higher degree of brittleness than originally estimated.

The cutter costs included in the preliminary performance estimates were derived from previously published data on quartz content and rock texture from thin-section petrographic analyses. The Cerchar abrasivity index (CAI) test, a more direct indicator of rock abrasivity, shows that the welded tuff is slightly less abrasive than originally estimated. Lower abrasivity, lower tensile strength, and higher brittleness result in significantly lower cutter costs than the initial estimation (Appendix A). Note that cutter costs decline as machine penetration rate increases because more material volume is excavated per unit time the excavator is running.

4.2 Results

The revised performance predictions for the mechanical excavators selected for this study are shown in Tables 4-1 through 4-10. They also are displayed graphically in Figures 4-1 through 4-8. The utilization factors developed during the preliminary study have not been changed. They are affected by many factors, principally machine backup system, excavation grades, and excavation curves. The effects of these factors on utilization

Table 4-1

Revised Performance Prediction of Two Tunnel Boring Machine (TBM) Configurations in the Potential Repository Horizon (TSw2)

Parameter	Standard TBM	High-Power TBM
Cutterhead diameter (ft)	25	25
Rotational speed (rpm)	6.36	7.0
Cutters (# @ diameter [in.])	50 @ 17	47 @ 19
Maximum cutter load (lbf)	50,000	60,000
Cutterhead power (# motors @ hp)	6 @ 400	7 @ 450
Maximum operating torque (ft-lbf)	1,982,000	2,026,000
Operating thrust (lbf)	2,500,000	2,820,000
Penetration per revolution (in.)	0.24	0.35
Penetration rate (ft/hr)	7.63	12.25
Cutter life (hr)	74	86
Tunnel length per cutter (ft)	421	750
Approximate cutter costs ($/yd^3)	4.83	4.37

are illustrated in Tables 4-2 and 4-5, for advance rates for the TBMs and the Mobile Miner, respectively. Appendix A contains a detailed discussion of this topic.

The revised predictions resulted in higher performance for all the mechanical excavators considered in this study, due to the lower tensile strength and higher degree of brittleness determined through the laboratory tests.

The revised performance predictions for the 25-ft (7.6-m) diameter standard and high-power TBMs are shown in Table 4-1. The new penetration rates are 7.6 and 12.3 ft/hr (2.3 and 3.7 m/hr), respectively. The cutter costs are lower than initially predicted for both machines because of the higher penetration rates. Cutter life and the resultant replacement costs primarily are functions of the distance traveled by individual cutters during the boring operation. Thus, higher penetration rates mean that cutters excavate larger volumes of material before wearing out. Table 4-2 lists the revised predictions for the advance rate for both the standard and the high-power TBMs. These predictions include estimated utilization factors for various combinations of slope angle, curve radius, and muck haulage system. A detailed discussion of factors that affect utilization estimates is given in Appendix A. As expected, a nearly horizontal tunnel with a slight upslope combined with rail haulage provides the highest utilization for both machines. Although the conveyor system at its present state of development gives a slightly lower utilization, it still may be preferred because it provides more free space in the tunnel during construction. Moreover, by using conveyor haulage, site characterization

Table 4-2

Revised Advance Rates of Two TBM Configurations in the Potential Repository Horizon (TSw2)[1]

	Scenario Number	Slope Percent	Curve Radius (ft)	Backup System	Penetration Rate (ft/hr)	Utilization Percent	Advance Rate (ft/day)
Standard TBM:	1	+1	None	Rail	7.6	55	101
	2	+1	None	Conveyor	7.6	50	92
	3	-9	None	Conveyor	6.3	45	68
	4	-14	None	Conveyor	5.6	40	54
	5	-21	None	Conveyor	5.3	35	45
	6	+1	600	Rail	4.7	35	39
	7	-15	600	Conveyor	4.3	30	31
High-Power TBM:	1	+1	None	Rail	12.3	55	162
	2	+1	None	Conveyor	12.3	50	147
	3	-9	None	Conveyor	10.5	45	113
	4	-14	None	Conveyor	9.8	40	94
	5	-21	None	Conveyor	9.5	35	80
	6	+1	600	Rail	7.0	35	59
	7	-15	600	Conveyor	7.0	30	50

[1]Each scenario changes one condition likely to be encountered during construction.

Table 4-3

Revised Performance Prediction of Two TBM Configurations in All Tuff Units

	Unit[2]	Instantaneous Penetration (in./rev)	Penetration Rate (ft/hr)	Advance Rate (ft/day)	Cutter Life (hr)	Cutter Life (ft of tunnel)	Cutter Costs ($/yd^3)
Standard TBM:	TSw1 (LR)	0.70	22.3	294	202	4,506	0.73
	TSw1 (G-2)	0.18	5.6	74	62	344	5.91
	TSw1 (GU-3)	0.44	14.0	185	98	1,369	1.67
	TSw2	0.24	7.6	101	74	421	4.83
	TSw3 (G-2)	0.62	19.7	260	113	2,226	1.10
	TSw3 (G-4)	0.40	12.7	168	94	1,195	1.87
	CHnlv	0.31	9.7	128	86	836	2.56
	CHnlz	0.70	22.3	294	160	3,565	0.82
High-Power TBM:	TSw1 (LR)	0.75	26.2	346	224	5,889	0.96
	TSw1 (G-2)	0.22	7.7	102	68	525	6.24
	TSw1 (GU-3)	0.55	19.2	253	109	2,091	1.78
	TSw2	0.35	12.3	162	86	750	4.37
	TSw3 (G-2)	0.75	26.2	346	125	3,289	1.22
	TSw3 (G-4)	0.50	17.5	231	104	1,821	2.01
	CHnlv	0.37	12.9	170	95	1,230	2.79
	CHnlz	0.75	26.2	346	177	4,642	1.05

[1]Excavating a level, 25-ft (7.6-m) diameter drift with no curves (utilization 55 percent)
[2]See Table 2-1 for rock unit codes.

Table 4-4

Revised Performance Prediction of Mobile Miners in Two Opening Shapes in the Potential Repository Horizon (TSw2)

Parameter	14 ft x 22 ft Opening	16 ft x 30.5 ft Opening
Cutterhead diameter (ft)	14	16
Width of cut (ft)	22	30.5
Sweep radius (ft)	19	22.5
Sweep angle (degrees)	68.5	82
Rotational speed (rpm)	14	11
Cutters (total/center/gage)	15/7/8	15/7/8
Cutterhead power (# motors @ hp)	2 @ 350	2 @ 450
Maximum operating torque (ft-lbf)	262,000	429,700
Penetration per sweep (in.)	0.39	0.43
Sweep time (sec)	25.5	35
Plunge time (sec)	3	3
Penetration rate (ft/hr)	4.20	3.36
Cutter life (hr)	75	78
Tunnel length per cutter (ft)	262	217
Approximate cutter cost ($/yd^3)	7.80	7.22

work is not interrupted by passing muck trains. Note, however, that a rail system will be required to transport supplies and personnel to the heading even in a tunnel using conveyor muck haulage.

As shown in Table 4-2, a high-power TBM excavating a straight, relatively horizontal tunnel is predicted to achieve a daily advance of 160 ft (49 m). Under the same conditions, the daily advance for the standard TBM is estimated to be 101 ft (31 m).

Table 4-3 lists the predicted TBM advance rates and cutter costs for excavation in other thermomechanical units present at the potential repository site. Naturally, very high advance rates and low cutter costs are feasible in the softer, nonwelded tuff units. In fact, in some of the lower strength units, machine performance primarily is controlled by the available capacity of the muck haulage system. With present haulage technology, the maximum penetration rate in the most excavatable units is estimated to be about 25 to 27 ft/hr (7.6 to 8.2 m/hr). The amount of lithophysae present in the rock also affects excavatability; contrast the predicted penetration rates listed in Table 4-3 for the three TSw1 locations (LR is lithophysae-rich).

The revised performance predictions for the two Mobile Miners in the potential repository horizon are summarized in Table 4-4. Again, they are higher than the preliminary predictions discussed in Appendix A. Cutter costs also are reduced due to higher penetration rates for both sizes of

Table 4-5

Revised Advance Rates of the Mobile Miner in Two Opening Sizes in the Potential Repository Horizon (TSw2)[1]

	Scenario Number	Slope Percent	Curve Radius (ft)	Rock Quality Designation Percent	Penetration Rate (ft/hr)	Utilization Percent	Advance Rate (ft/day)
14 ft by 22 ft Opening:	1	+1	None	50+	4.2	40	40
	2	+1	None	25 to 50	4.2	30	30
	3	-9	None	50+	4.2	35	35
	4	-18	None	50+	4.2	30	30
	5	-15	None	25 to 50	4.2	24	24
	6	+1	100	50+	3.6	30	26
	7	-15	100	50+	3.6	27	23
16 ft by 30.5 ft Opening:	1	+1	None	50+	3.4	45	36
	2	+1	None	25 to 50	3.4	35	28
	3	-9	None	50+	3.4	40	32
	4	-18	None	50+	3.4	37	30
	5	-15	None	25 to 50	3.4	30	24
	6	+1	100	50+	2.8	35	23
	7	-15	100	50+	2.8	33	22

[1]Each scenario changes one condition likely to be encountered during construction.

Table 4-6

Revised Performance Prediction of Heavy-Duty Roadheaders in Two Opening Sizes in the Potential Repository Horizon (TSw2)

Parameter	22 ft by 12.5 ft Opening	15 ft by 21.5 ft Opening
Cutterhead diameter (in.)	47	47
Rotational speed (rpm)	55	55
Cutters	Sandvik SYS35	(drag type)
Cutter penetration angle (degrees)	56	56
Cutter spacing (in.)	2.0	2.0
Cutter speed (ft/min)	680	680
Maximum cutter load (lbf)	30,000	30,000
Cutterhead power (hp)	400	400
Penetration per sweep (in.)	0.4	0.4
Penetration rate (ft/hr)	1.72	1.22
Approximate cutter costs ($/yd^3)	10.75	10.75

Table 4-7

Revised Performance Prediction of Two Blind Shaft Borer (BSB) Speeds in the Potential Repository Horizon (TSw2)

Parameter	High Speed	Low Speed
Cutterhead diameter (ft)	18	18
Rotational speed (rpm)	8.2	6.15
Cutters (# @ diameter [in.])	35 @ 17	35 @ 17
Maximum cutter load (lbf)	50,000	50,000
Cutterhead power (# motors @ hp)	3 @ 375	3 @ 375
Maximum operating torque (ft-lbf)	720,500	960,700
Operating thrust (lbf)	1,750,000	1,750,000
Penetration/revolution (in.)	0.15	0.20
Penetration rate (ft/hr)	6	6
Cutter life (hr)	86	116
Shaft length per cutter (ft)	515	698
Approximate cutter cost ($/yd^3)	7.51	5.54

Table 4-8

Revised Performance Prediction of a Vertical Wheel Shaft Boring Machine (SBM) in the Potential Repository Horizon (TSw2)

Parameter	
Cutterwheel diameter	18 ft
Rotational speed	9 rpm
Traverse speed	0.95 rpm (around shaft)
Cutters	16 @ 17-in. diameter
Cutter spacing	4.0 in. (at perimeter)
Maximum cutter load	50,000 lbf
Cutterhead power	2 motors @ 400 hp
Maximum operating torque	396.8 by 10^3 ft-lbf
Operating thrust	348 by 10^3 lbf
Penetration per traverse	1.05 in.
Penetration rate	4.95 ft/hr
Cutter life	28 hr
Shaft length per cutter	118 ft
Approximate cutter costs	4.87 $/yd^3$

Table 4-9

Revised Performance Prediction of Two Sizes of Raise Drills in the Potential Repository Horizon (TSw2)

	Raise Diameter	
Parameter	18 ft	6 ft
Pilot string diameter (in.)	12.875	10
Pilot bit diameter (in.)	13.75	11
Reaming head diameter (ft)	18	6
Rotational speed (rpm)	6	10
Cutters with tungsten-carbide inserts (# cutters @ # disks/cutter)	26 @ 4	10 @ 4
Cutter spacing (in.)	2.0	2.0
Maximum cutter load (lbf)	50,000	65,800
Cutterhead power (hp)	400	300
Maximum operating torque (ft-lbf)	258,500	44,100
Operating thrust (lbf)	1,307,000	492,300
Penetration/revolution (in.)	0.09	0.10
Penetration rate (ft/hr)	2.58	9.15
Cutter life (hr)	604	518
Shaft length per cutter (ft)	1382	4212
Approximate cutter costs ($/yd^3)	17.13	16.11

Table 4-10

Revised Performance Prediction of Two V-Mole Configurations in the Potential Repository Horizon (TSw2)

Parameter	V-Mole Standard	V-Mole Upgraded
Cutterhead diameter (ft)	18	18
Rotational speed (rpm)	6	8
Cutters (# @ diameter [in.])	34 @ 14	23 @ 17
Maximum cutter load (lbf)	35,000	50,000
Cutterhead power (hp)	900	1200
Maximum operating torque (ft-lbf)	551,500	669,600
Operating thrust (lbf)	1,190,000	1,150,000
Penetration/revolution (in.)	0.18	0.23
Penetration rate (ft/hr)	5.61	9.36
Cutter life (hr)	81	68
Tunnel length per cutter (ft)	392	549
Approximate cutter costs ($/yd^3)	12.87	5.09

opening. The higher penetration rates translate into higher daily advance rates, as shown in Table 4-5. The procedure used to determine utilization factors for calculating advance rates is discussed in Appendix A. As with TBM operations, a straight, horizontal excavation with a slight upslope provides for the highest machine utilization, and consequently, for the maximum attainable advance rate.

Table 4-6 presents the revised performance estimates for a heavy-duty roadheader excavating two differently sized openings. Even with the upgraded performance results, the roadheader is able to achieve only low productivity in the potential repository horizon, with attendant high bit costs. However, as discussed earlier, roadheaders are highly flexible and versatile, with the capability to cut variously sized and shaped openings while offering high mobility and ready access to the tunnel face. In the potential repository horizon, roadheaders at their present state of development may not provide an economically attractive means of excavation for long tunnels or drifts where high production rates are required. They can, however, prove extremely useful for excavating chambers, test rooms, crosscuts, or alcoves. Naturally, roadheaders are expected to attain much higher production rates in the lower strength, nonwelded tuff units at the Yucca Mountain site.

For the full-face BSB, the preliminary performance predictions already had reached the limits imposed by the backup systems, including muck removal and shaft lining. The penetration rate is fixed at a maximum of 6.0 ft/hr (1.8 m/hr) for a daily advance of 40 ft (12.2 m). This is based on the current capabilities of shaft lining systems, which generally are limited to installation of two 20-ft (6.1-m) liner sections per day. Because the

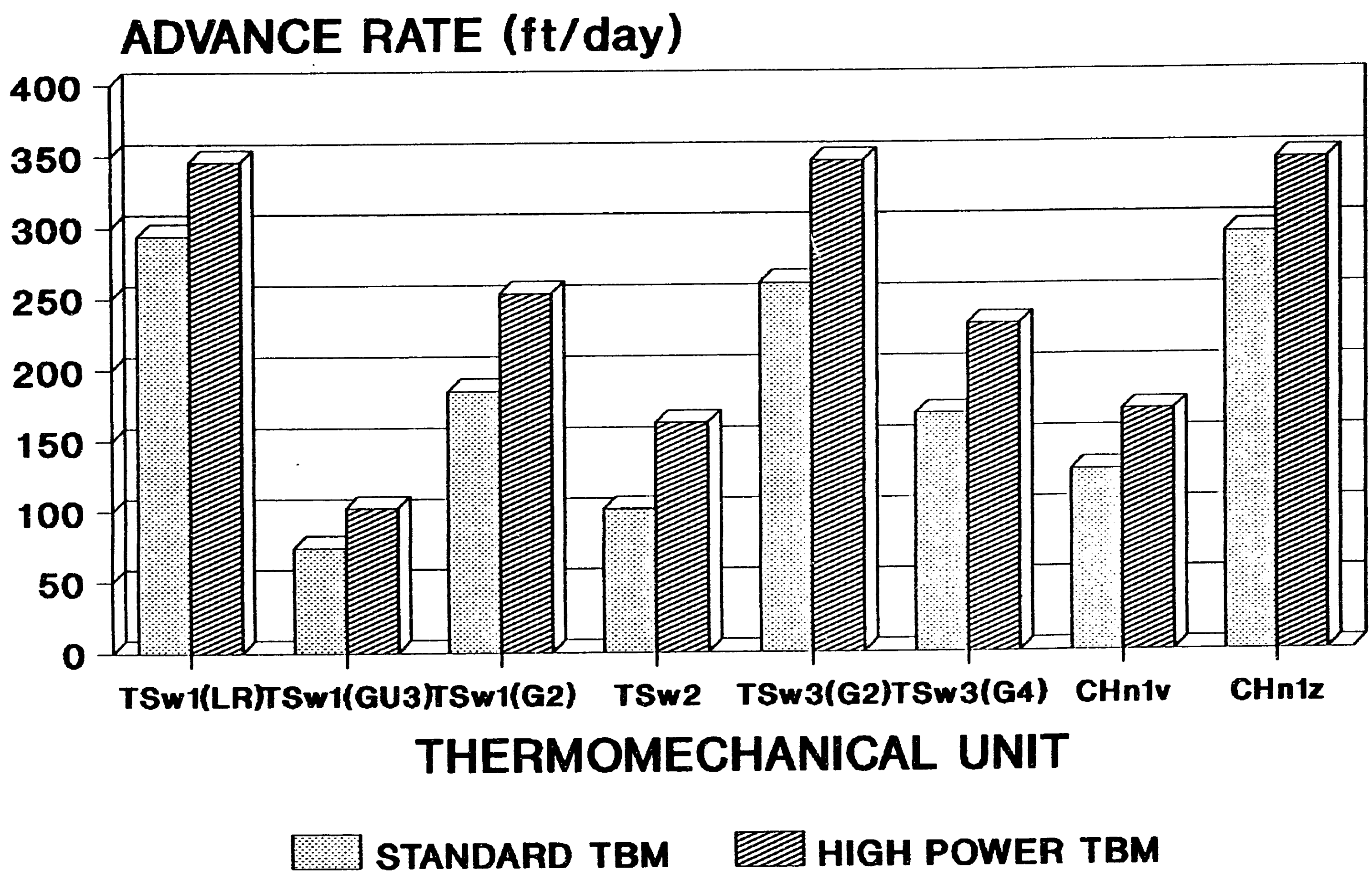

Figure 4-1. Revised TBM Advance Rates For All Tuff Units Considered

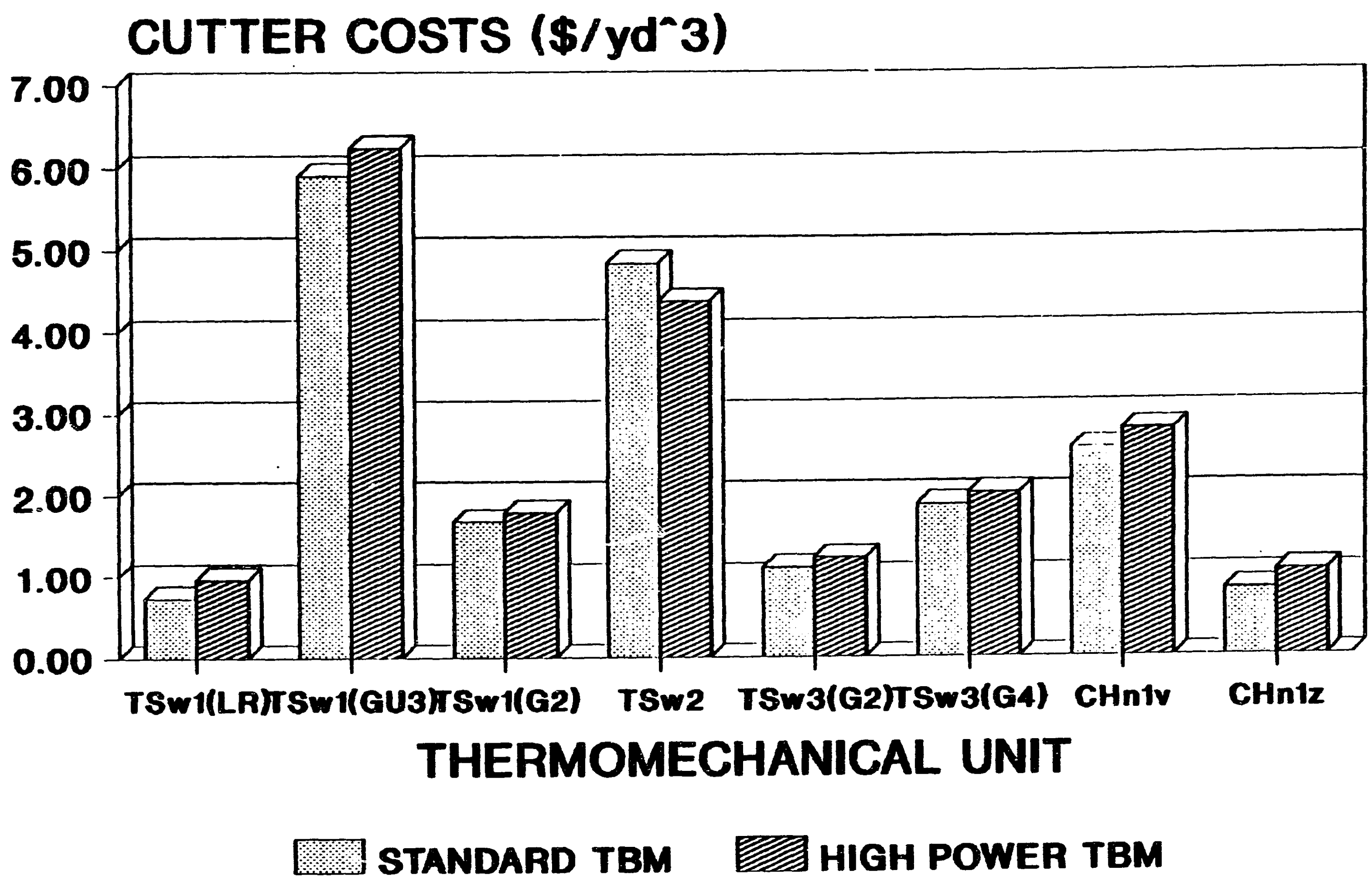

Figure 4-2. Revised TBM Cutter Costs For All Tuff Units Considered

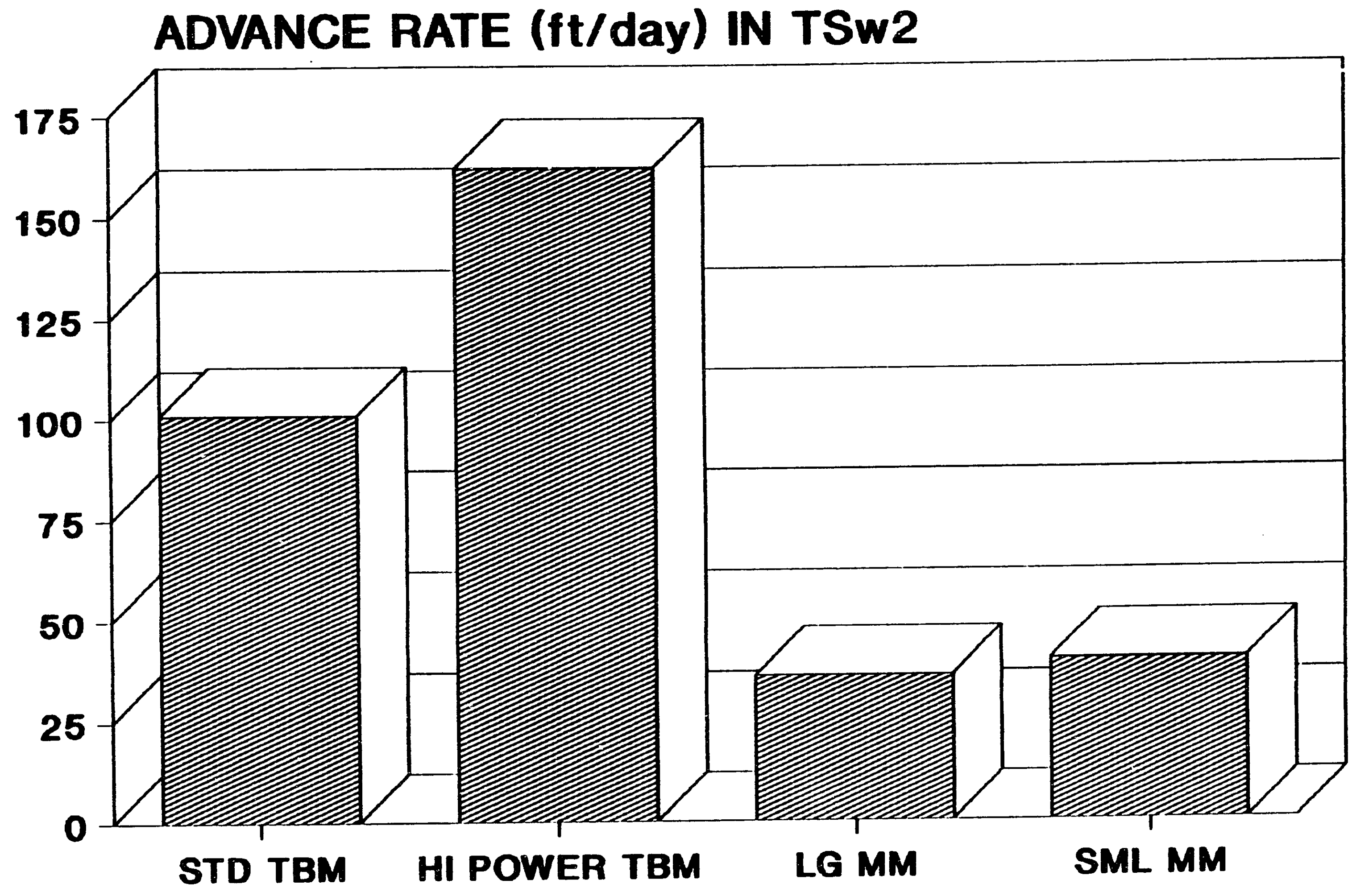

Figure 4-3. Revised Advance Rates For Horizontal Excavators in the Potential Repository Horizon (TSw2)

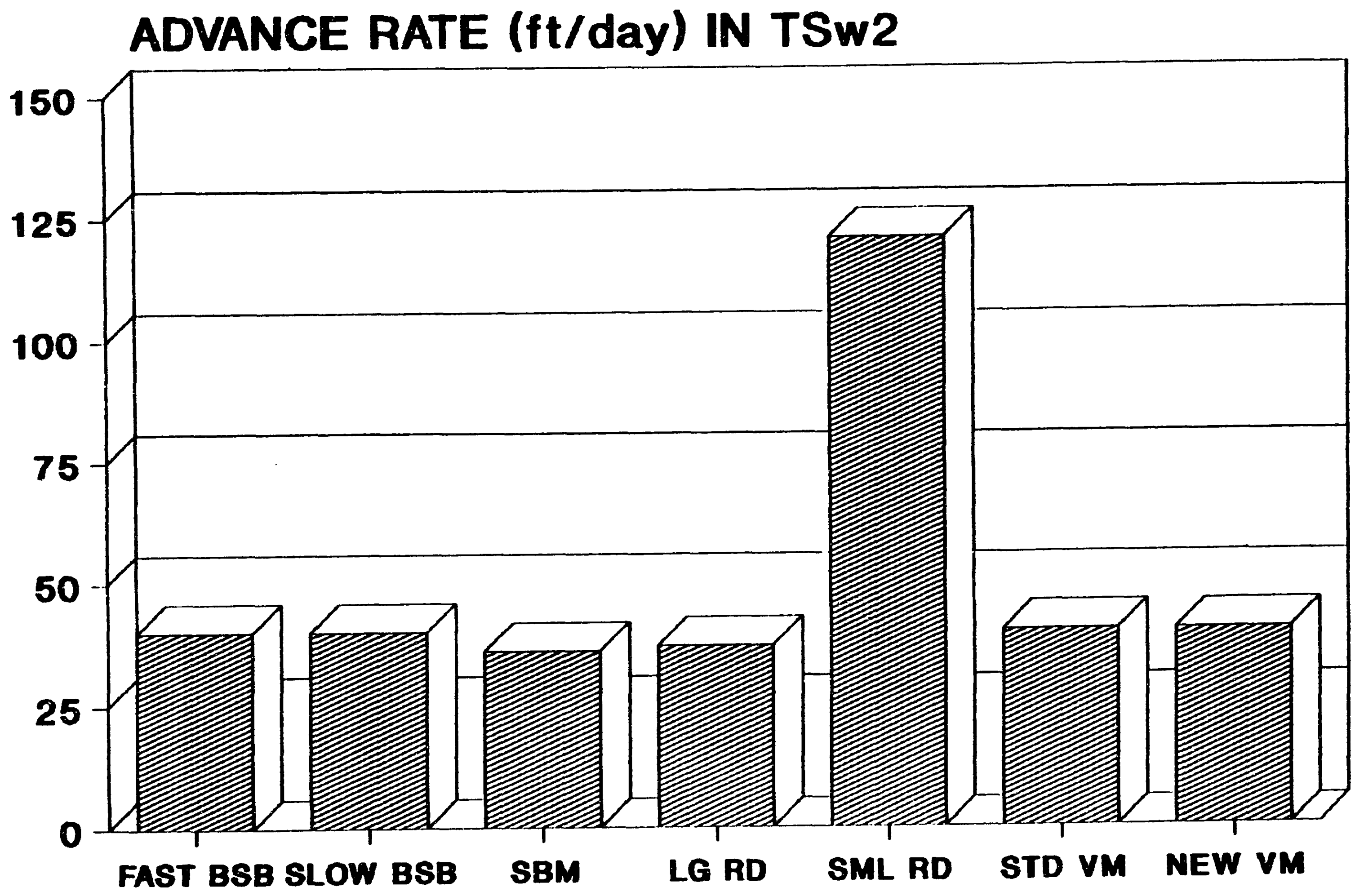

Figure 4-4. Revised Advance Rates For Shaft Borers in the Potential Repository Horizon (TSw2)

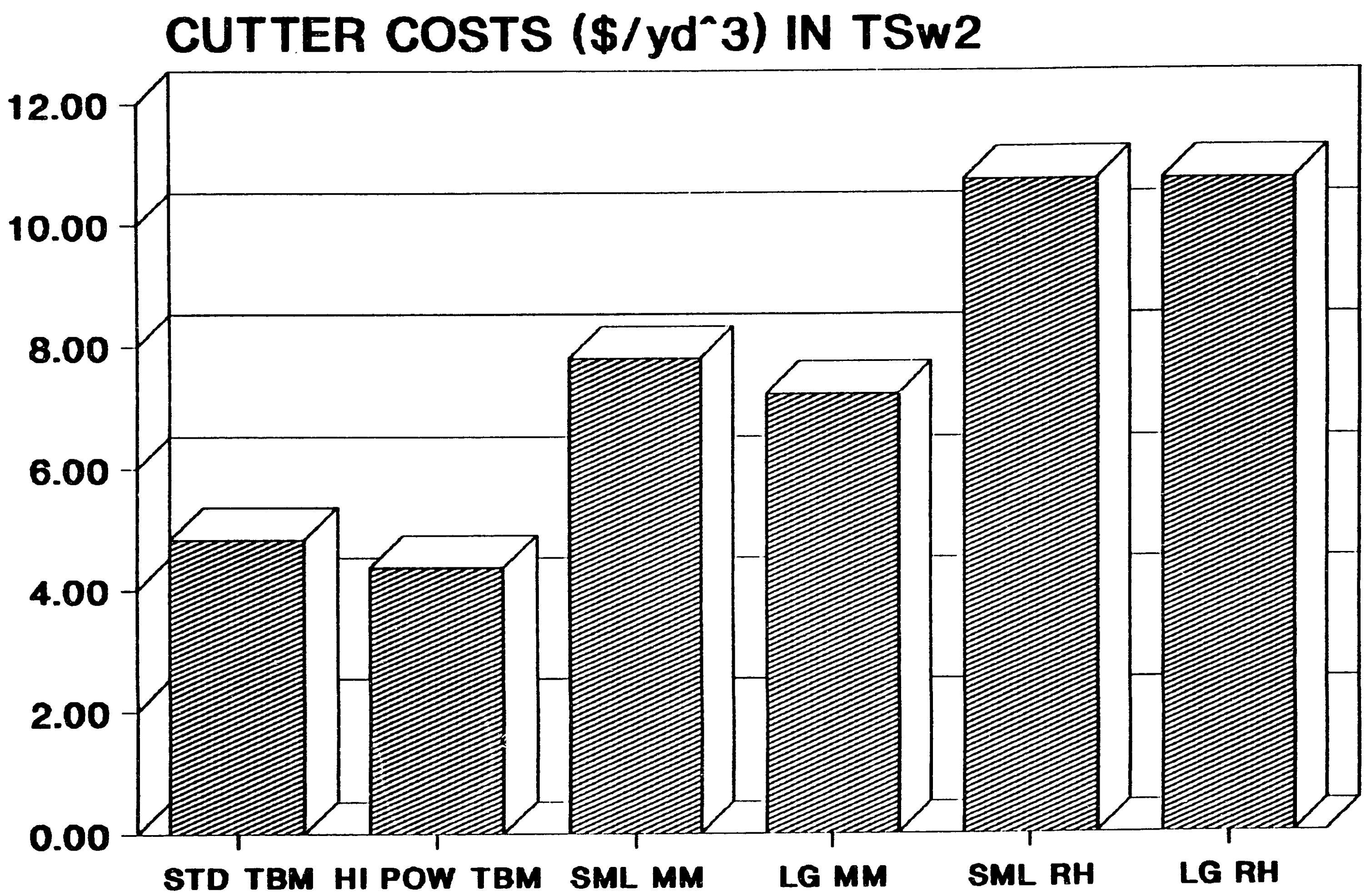

Figure 4-5. Revised Cutter Costs For Horizontal Excavators in the Potential Repository Horizon (TSw2)

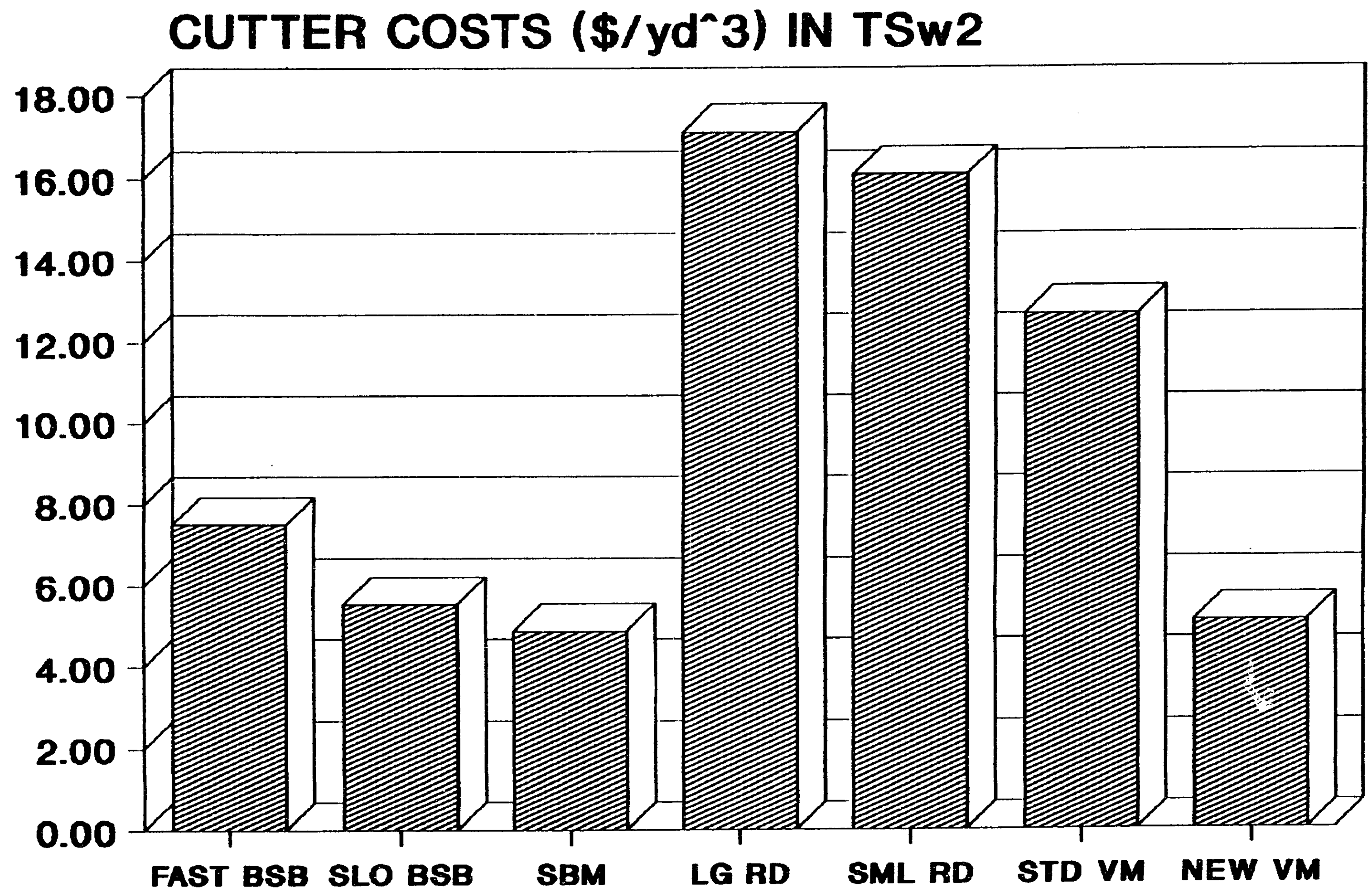

Figure 4-6. Revised Cutter Costs For Shaft Borers in the Potential Repository Horizon (TSw2)

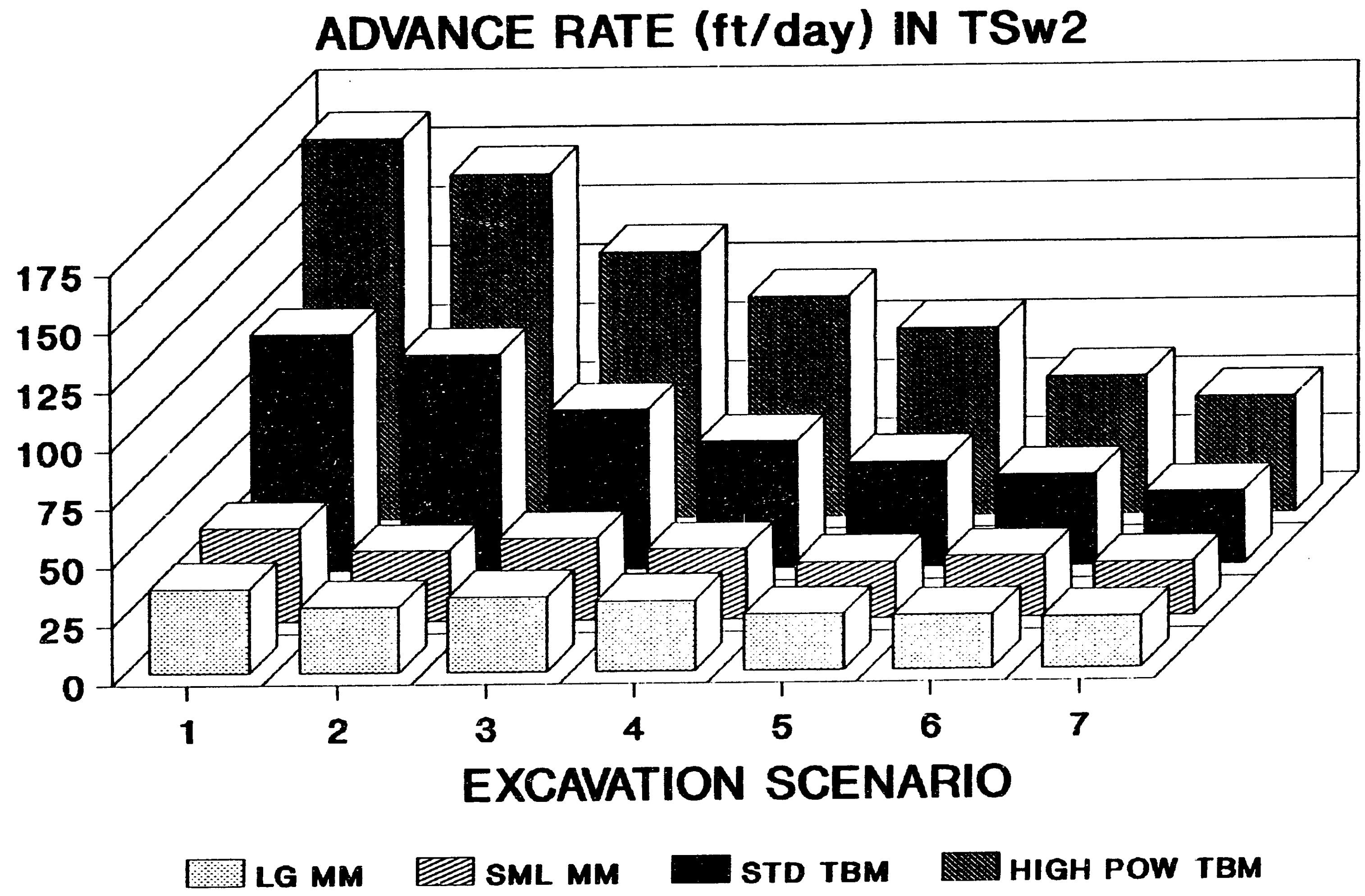

Figure 4-7. Effect of Excavation Design and Rock Conditions on TBM and Mobile Miner Advance Rates in the Potential Repository Horizon (TSw2)

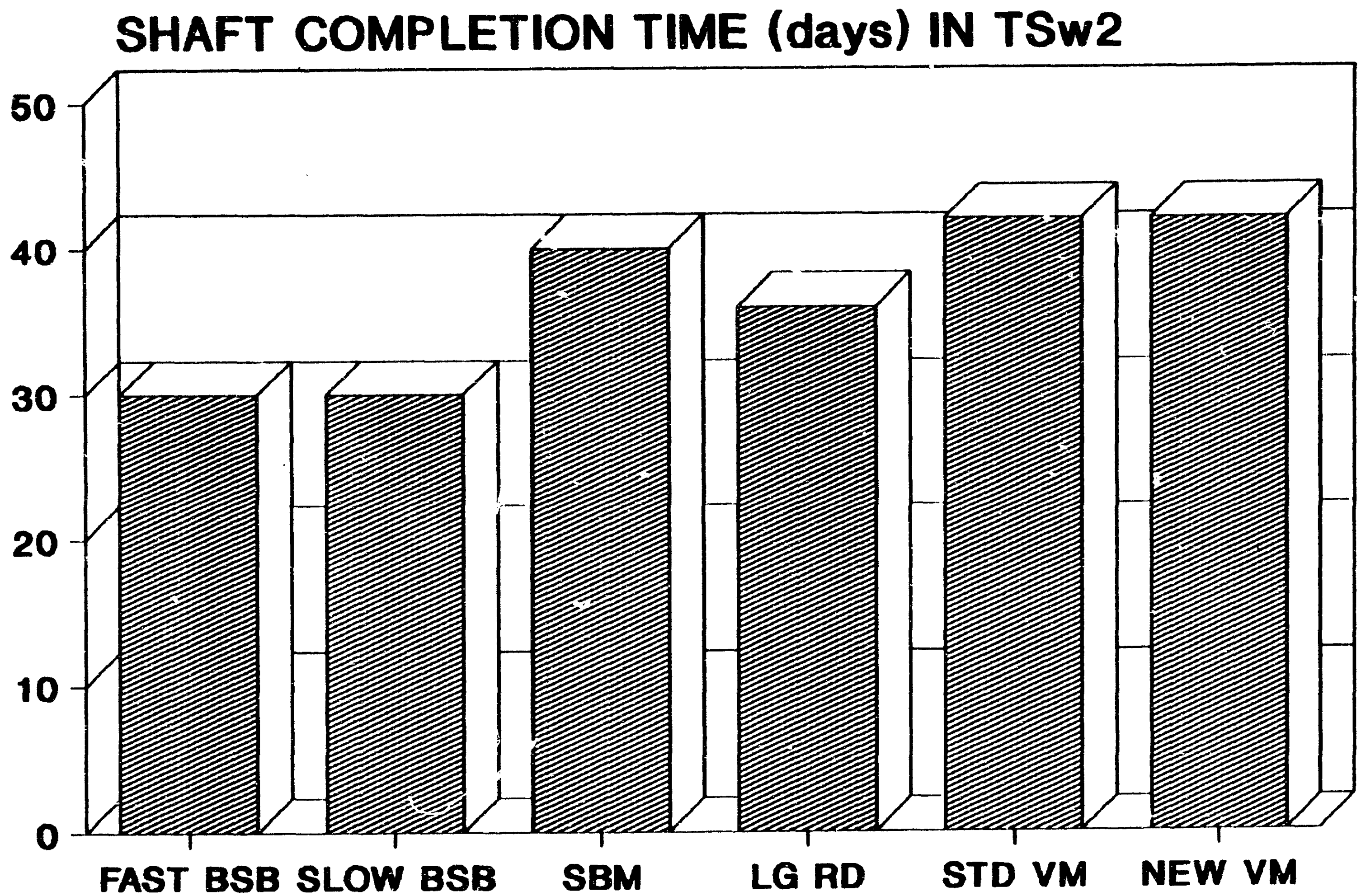

Figure 4-8. Estimated Time to Completion of Shaft Borers in the Potential Repository Horizon (TSw2)

original performance estimates for the BSB already were governed by the lining speed, the new rock property data showing easier cutability did not result in production rate increases. However, the enhanced boreability of the potential repository horizon did reduce the cutter costs from the initial predictions, as shown in Table 4-7.

Table 4-8 summarizes the revised performance predictions for the vertical wheel SBM. The new penetration rate is estimated to be 5.0 ft/hr (1.5 m/hr), with cutter costs of $4.87/yd^3 ($5.33 m^3). As noted earlier, the SBM is a partial-face excavator, meaning that it cuts only a portion of the shaft bottom at a time. As a result, it is not capable of matching the production capacity offered by the BSB. From the perspective of repository site characterization, the SBM has a unique advantage over the BSB in that it provides ready personnel access to the shaft bottom. Further, the SBM offers more options for implementation of various muck pickup and removal techniques. For these reasons, it may prove to be a more effective shaft excavator for the potential repository.

Table 4-9 lists the revised performance estimates for two sizes of raise drills in the potential repository horizon. The small one is intended to drill the pilot hole for a V-Mole (below). It now is expected to achieve a penetration rate of 9.2 ft/hr (2.8 m/hr). The large drill, which excavates the entire diameter of the shaft, will penetrate 2.6 ft/hr (0.8 m/hr). The cutter costs for both raise drills are lower than initially estimated, due again to the higher penetration rates.

The revised performance predictions for the standard and upgraded V-Moles are presented in Table 4-10. The new estimates show that the upgraded version can achieve a penetration rate of 9.4 ft/hr (2.9 m/hr), while the standard machine can achieve 5.6 ft/hr (1.7 m/hr). As discussed previously, the V-Mole uses a raise-bored pilot hole for muck removal, so its cutting efficiency is not hindered by muck buildup at the face. Muck buildup is likely to occur with the BSB.

Many of these results also are presented in the form of graphs. Figures 4-1 and 4-2 illustrate the projected advance rates and cutter costs for the two TBM configurations in several of the tuff units found at Yucca Mountain, repeating the data presented in Table 4-3. Figures 4-3 through 4-6 compare the projected advance rates and cutter costs of all the excavators, concentrating on the potential repository horizon. The advance rates for the TBMs and the Mobile Miner under various construction conditions, originally presented in Tables 4-2 and 4-5, are illustrated graphically in Figure 4-7. Figure 4-8 compares total shaft construction time using the four shaft excavators under ideal conditions. This is intended for comparison between these machines only, not as a proposed schedule for shaft construction.

5.0 CONCLUSIONS

Various mechanical excavation systems are being evaluated for use in the construction of the ESF, which will provide access to the potential repository block for conducting site characterization studies. This report is the first of a series reporting the work performed by Earth Mechanics Institute (EMI) for SNL. The main objective of this effort is to characterize and predict the performance of several mechanical excavation systems in the various tuff units of the Yucca Mountain site, emphasizing TSw2. The systems considered for performance assessment include tunnel boring machines, the Mobile Miner, roadheaders, the blind shaft borer, the vertical wheel shaft boring machine, raise drills, and the V-Mole.

The performance predictions reported here are based on empirical and theoretical relationships developed by EMI between certain physical properties of the rock and the forces experienced by the different types of cutters and bits utilized by various mechanical excavators. The methodology then calculates the thrust, torque, and power required by the particular machine to provide those forces.

The work was performed in three phases: (1) performance prediction based on rock physical property data already published in the RIB, Version 4; (2) measurement of several additional rock properties known to influence excavator design; and (3) refinement of the preliminary predictions using the newly acquired data.

Incorporation of measured abrasivities, compressive-to-tensile strength ratios, and force-penetration test results for the potential repository horizon (TSw2) into the initial predictions resulted in performances higher than first estimated. In particular, the laboratory test results revealed that the welded tuff behaves in a more brittle manner than originally apparent, thus allowing more efficient cutting by mechanical excavators. Refinement of performance predictions using the new physical property data increases the tunnel boring machine advance rate 30 percent to 40 percent over the initial predictions. The cutter costs decrease by 12 percent to 15 percent.

All the mechanical excavation systems analyzed can excavate the tuffs of the Yucca Mountain site successfully. The revised performance estimates for horizontal mechanical excavators operating in the potential repository horizon (TSw2) are as follows:

- The 25-ft (7.6-m) diameter standard tunnel boring machine (TBM) will advance 101 ft/day (31 m/day), with cutter costs of $4.83/yd^3 ($5.28/m^3).

- The 25-ft (7.6-m) diameter high-power TBM will advance 162 ft/day (49 m/day), with cutter costs of $4.37/yd^3 ($4.78/m^3).

- The Mobile Miner will advance 40 ft/day (12 m/day) in the small (14 ft by 22 ft or 4.3 m by 6.7 m) opening, with cutter costs of $7.80/yd^3 ($8.53/m^3).

- The Mobile Miner will advance 36 ft/day (11 m/day) in the large (16 ft by 30.5 ft or 4.9 m by 9.3 m) opening, with cutter costs of $7.22/yd^3$ ($7.90/m^3$).

- The heavy-duty roadheader will advance < 41 ft/day (12.5 m/day) in the small (22 ft by 12.5 ft or 6.7 m by 3.8 m) opening, with cutter costs of $11.60/yd^3$ ($12.69/m^3$).

- The heavy-duty roadheader will advance < 29 ft/day (5.8 m/day) in the large (15 ft by 21.5 ft or 4.6 m by 6.6 m) opening, with cutter costs of $12.50/yd^3$ ($13.67/m^3$).

Within the limits imposed by muck removal and shaft lining (40 ft/day or 12 m/day), the shaft borers are estimated to perform as follows:

- The 18-ft (5.5-m) diameter blind shaft borer (BSB) will advance 40 ft/day (12 m/day) at low speed, with cutter costs of $5.54/yd^3$ ($6.06/m^3$).

- The 18-ft (5.5-m) diameter BSB will advance 40 ft/day (12 m/day) at high speed, with cutter costs of $7.51/yd^3$ ($8.21/m^3$).

- The 18-ft (5.5-m) diameter vertical wheel shaft boring machine (SBM) will advance 36 ft/day (11 m/day), with cutter costs of $4.87/yd^3$ ($5.33/m^3$).

- The 18-ft (5.5-m) diameter raise drill will advance 37 ft/day (11 m/day), with cutter costs of $17.13/yd^3$ ($18.73/m^3$).

- The 6-ft (1.8-m) diameter raise drill will advance 121 ft/day (37 m/day), with cutter costs of $16.11/yd^3$ ($17.62/m^3$), excavating a pilot hole for the V-Mole (below).

- The 18-ft (5.5-m) diameter standard V-Mole (after pilot hole is drilled) will advance 40 ft/day (12 m/day), with cutter costs of $12.67/yd^3$ ($13.86/m^3$).

- The 18-ft (5.5-m) diameter upgraded V-Mole (after pilot hole is drilled) will advance 40 ft/day (12 m/day), with cutter costs of $5.09/yd^3$ ($5.57/m^3$).

Note that the shaft excavation rate is limited by the support systems, particularly shaft lining and muck removal, to 40 ft/day (12 m/day), although the excavators themselves are capable of achieving much higher rates of advance.

The evaluations based on physical property and punch indentation tests show that the welded tuffs are highly suitable for efficient excavation by mechanical means. However, for efficient excavation to occur, the analysis shows that the cutter loads and the resulting penetrations have to be sufficiently high to take advantage of the brittleness which the rock exhibits at high penetrations. In other words, the TSw2 tuff unit requires deeper tool penetrations for initiation of rock chipping, in comparison with rocks of similar compressive strength.

6.0 RECOMMENDATIONS

The next recommended stage in predicting the performance of mechanical excavators in Yucca Mountain tuffs is to measure the actual cutter forces needed to fracture the tuff. These measurements can be obtained with the Colorado School of Mines (CSM) Linear Cutting Machine (LCM) using standard disk and point attack cutters with large tuff samples from the Yucca Mountain site. Various promising combinations of cutter spacing and penetration can be tested directly with this equipment. The best combinations are those which produce the largest volume of rock chips using the least amount of specific cutting energy. This energy is expended by the normal, rolling (or drag), and side forces experienced by the cutters. In the present study, these forces are estimated indirectly from the physical properties of the rock. Results of the LCM studies will be used for enhanced predictions and will be summarized in a subsequent technical report.

Following selection of spacing-to-penetration ratios for the various cutters from the LCM tests, a possible next step is to conduct full-scale tests of complete cutterhead designs incorporating these ratios. This could be done with the CSM Laboratory Tunnel Boring Machine (LTBM). This device, which is designed to simulate closely the field performance of mechanical excavators, permits direct physical measurement of the efficiency of a cutterhead. The results of tests using the LTBM include the effects of lacing pattern, cutter wear, and other factors included only indirectly in previous predictive analyses. The bored sample also can provide a useful testbed for conducting geologic mapability studies of machine-excavated openings.

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APPENDIX A

EXCAVATOR PERFORMANCE PREDICTIONS
USING EXISTING DATABASES

by

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(Formerly SLTR90-7003)

Submitted 15 February 1991

QUALITY ASSURANCE

The work discussed in this SLTR was conducted under the aegis of Work Breakdown Structure (WBS) element 1.2.4.2.1.3, titled "Rock Mechanics Field Testing." All efforts within this WBS element are scoping and developmental in nature, and therefore are considered nonquality affecting activities. However, several quality assurance implementing procedures were utilized in the conduct of this work to be consistent with the intent of the Sandia Quality Assurance Program Plan (QAPP).

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1.0 INTRODUCTION

1.1 Background

The work described here was performed under Task 1.1 of Contract 35-0039 for Sandia National Laboratories (SNL) as part of the Yucca Mountain Site Characterization Project (YMP). SNL is one of the principal organizations participating in the project, which is managed by the U.S. Department of Energy's (DOE) Nevada Operations Office. The project's purpose is to dispose safely of the radioactive waste from commercial nuclear power plants.

The DOE has determined that the safest and most feasible method currently known to dispose of such wastes is to place them in mined geologic repositories. Various means of excavating the repositories are being examined, including mechanical excavators. This report presents preliminary predictions of the performance of selected mechanical excavating systems in welded tuffs that represent potential repository horizons. The predictions are based on existing SNL rock property data and were interpreted by engineers experienced in specifying mechanical excavation systems.

1.2 Purpose

The primary purpose of this study was to make preliminary predictions of the expected performance of mechanical excavators operating in a variety of Yucca Mountain tuffs. This scoping study was divided into four steps:

1. A literature search was conducted on existing databases of the physical properties of Yucca Mountain welded tuffs.

2. Rock properties that affect mechanical excavation were assessed and the appropriate properties were selected for performance prediction.

3. Mechanical excavators were selected for performance assessment. A range of excavator types that are capable of constructing shafts, ramps, drifts, raises, and rooms was included.

4. Computer codes, manual calculations, and empirical methods were used to predict the mechanical excavator performance in the tuff layers of the Yucca Mountain site.

The predictions presented here emphasize the potential repository horizon, Topopah Spring welded tuff unit number two (TSw2) but include other rock types found at the site. Four types of mechanical excavation systems were evaluated: tunnel boring machines (TBMs), the Mobile Miner, roadheaders, and shaft borers. The results of the performance predictions lead in turn to recommendations for further tests of welded tuff properties to refine these performance estimates.

1.3 Goals

The primary goal of this report is to provide preliminary estimates of how selected mechanical excavators would be expected to perform in the welded tuffs that will be encountered during any construction at the Exploratory Shaft Facility (ESF) site. The estimates provided will assist the architect/engineers in preliminary scheduling and planning.

In addition, a discussion of available types of mechanical excavators and the terminology and practices of the tunneling industry has been included.

Due to the limited rock property data available, no attempt was made to perform a quantitative sensitivity analysis of the excavator performance factors. Sensitivity analyses may be included in later reports, where it will be based on a larger experimental data set.

1.4 Scope

Machinery performance estimates are based on certain assumptions. A brief discussion of these assumptions will aid in understanding the significance of the results presented in this report.

Preliminary feasibility studies are standard procedure in the mechanical excavation industry. This report is a preliminary feasibility study. This type of study determines if the project is technically and economically feasible, and if it is, indicates the expected performance of the excavator. A preliminary feasibility study collects the best available data, interprets the data using the best available expert advice, and predicts the performance of the excavator using the existing data. It is the initial and preliminary estimate available for the construction engineer. Necessarily, these estimates of performance must be refined before construction begins.

The predictions derived from this process can be very accurate. Both the quality of the data and the expert judgment determine the accuracy of the results. EMI personnel and the adjunct professors each have over ten years experience predicting excavator performance. As per standard practice, the performance predictions are intentionally conservative by approximately 10 percent.

Predictions made from limited databases are, by necessity, preliminary feasibility studies. A more complete database is needed before more detailed and reliable performance predictions are made. The complete database is based on tests more specific to mechanical excavator performance, rather than general rock property tests designed for basic science analysis. Furthermore, the complete database will be more specific to the machine-rock combination for the project.

1.5 Units

English units are the standard units used by mechanical excavator manufacturers and contractors in the United States. S.I. conversion factors are provided in Appendix II.

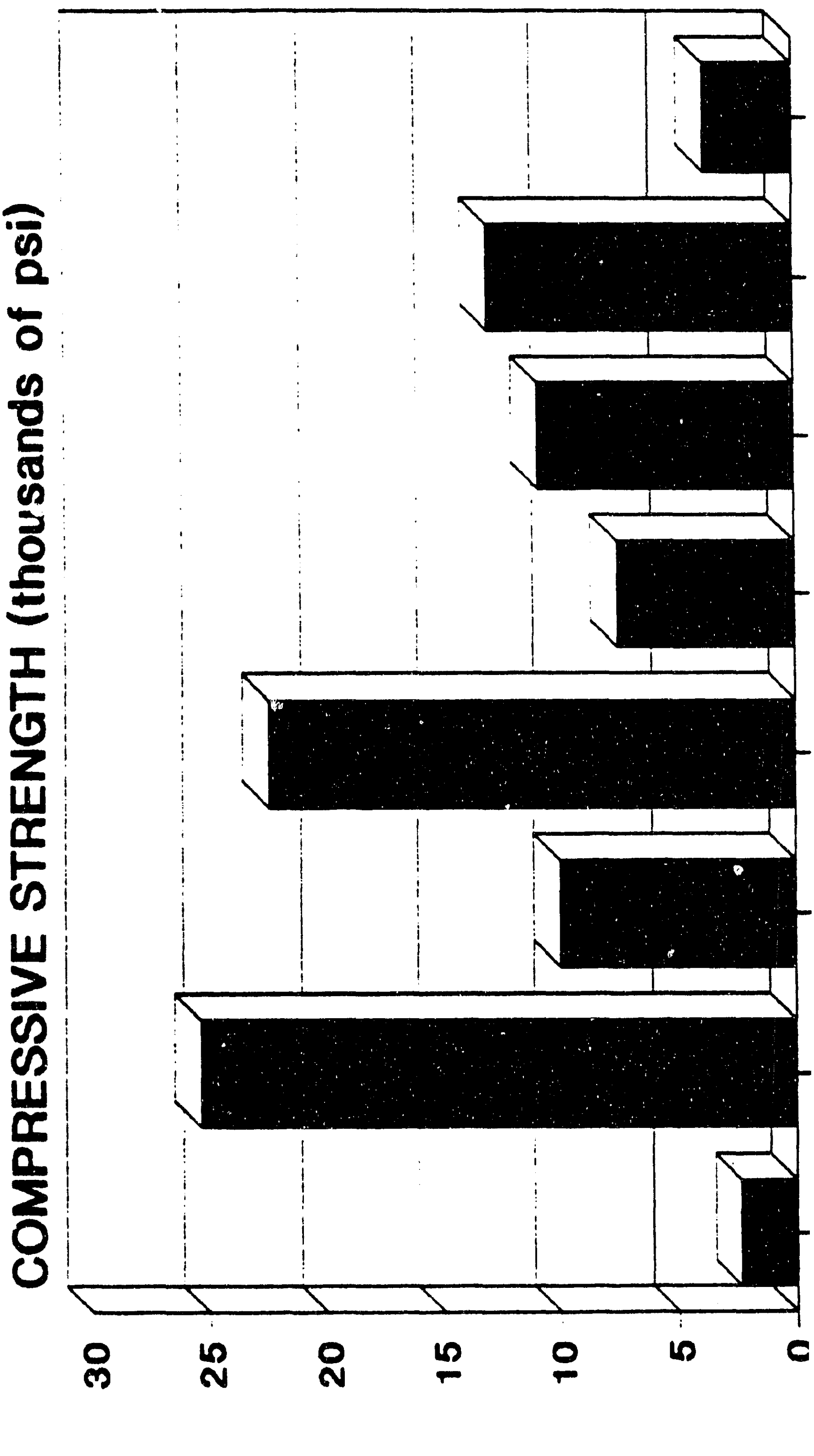
1.6 The Existing Database

Predicting excavator performance from the basic properties of rock requires a specific set of rock property data. The database of physical properties for the rock at the Yucca Mountain site contains much data that has little bearing on the excavatibility of the rock. On the other hand, some parameters which impact excavator performance prediction were not available in the published literature. Rock properties needed for input into the predictive model are uniaxial compressive strength (UCS), tensile strength, abrasivity, rock quality designation (RQD), and density, with UCS as the single most important value. Although not used directly in performance prediction, Young's modulus and Poisson's ratio values were examined. The use of these model input values is discussed in Section 1.4. The appropriate values were extracted from the Reference Information Database (RIB) Version 4 (USDOE, 1989). Table 1 and Figure 1 show the parameter ranges used in this study.

Table 1

Uniaxial Compressive Strengths Used For Performance Evaluation, From RIB Version 4 (USDOE, 1989) (TS - Topopah Spring, CH - Calico Hills, w - welded, n - nonwelded, v - vitric, z - zeolitized)

THERMOMECHANICAL UNIT	COMPRESSIVE STRENGTH (psi / MPa)
TSw1 (LR - lithophysae rich)	2,350 / 16
TSw1 (GU-3 - litho. poor, well USW GU-3)	10,000 / 175
TSw1 (G-2 - litho. poor, well USW G-2)	25,380 / 69
TSw2	22,480 +- 8,500 / 155 +- 59
TSw3 (USW G-2 - well USW G-2)	7,540 / 52
TSw3 (USW G-4 - well USW G-4)	10,880 / 75
CHnlv	13,050 / 90
Chnlz	3,770 / 26



COMPRESSIVE STRENGTH (thousands of psi)
30
25
20
15
10
5
0

Other data on the Yucca Mountain tuffs, available from published reports, also were examined. A large amount of uniaxial compressive strength values and other test results are reported in various SAND reports. These reports were useful for the EMI staff to gain an appreciation of the range of characteristics of the tuffs at Yucca Mountain. Price and Jones (1982) reported a UCS for the Calico Hills tuff ranging from 14.2 to 42.0 MPa (2059 to 6091 psi). Price et al. (1982) reported the UCS of members of the Topopah Spring welded tuffs as ranging from 44.9 to 176.6 MPa (6500 to 25,600 psi). Zimmerman and Finley (1987) provided a large amount of background data, including tensile and shear strength data.

Nimick and Schwartz (1987) was used to further the understanding of the welded tuffs, as was Nimick et al. (1985). Price et al. (1984 and 1985) added useful rock characterizations, including data on silica content. Nimick (1988) also provided background on silica content. Price (1983) provided an understanding of the porosity of the Topopah Spring tuffs. While not adding to the performance prediction empirical data set, these reports aided in understanding the potential repository rocks.

The data varied from test population to test population, a normal occurrence in rock physical property testing. This did cause some uncertainty as to the expected range of values, since comparisons between populations were difficult. Further, much of this work supported the data found in the RIB (USDOE, 1989). It was decided to use the values of UCS reported in the RIB. The RIB provides representative data that are in common use by Yucca Mountain Project participants. In addition, RQD values were extracted from Langkopf and Gnirk (1986). These values were variable and depth dependent, especially for the TSw tuffs; an RQD range of 50 to 75 was used. Density impacts the design of the backup system for mechanical excavators, as it determines the mass of the rock to be excavated and passed through the backup system.

The rock at Yucca Mountain includes welded and non-welded ash flow and air fall tuffs containing varying amounts of lithophysae (voids) and matrix devitrification (Figure 2). The ESF is planned to be constructed in the Topopah Spring welded tuff unit number two (TSw2), and the performance predictions emphasized this formation.

1.7 Excavation Equipment Considered

The ESF will consist of combinations of shafts, raises, drifts, ramps, alcoves, and chambers or rooms. To construct these diverse openings, four types of mechanical excavation machinery systems were evaluated in this study: tunnel boring machines, the Mobile Miner, roadheaders, blind shaft borers, raise borers, and V-Moles. Each machine type is better suited to excavating certain types of underground openings than others.

While the machines were selected in order to present a wide variety of types, their selection leads to a discussion of machine suitability for ESF construction. The discussions that follow below are based on common industry applications and practices. The unique requirements of this construction project will significantly impact the suitability of any mechanical excavating system.

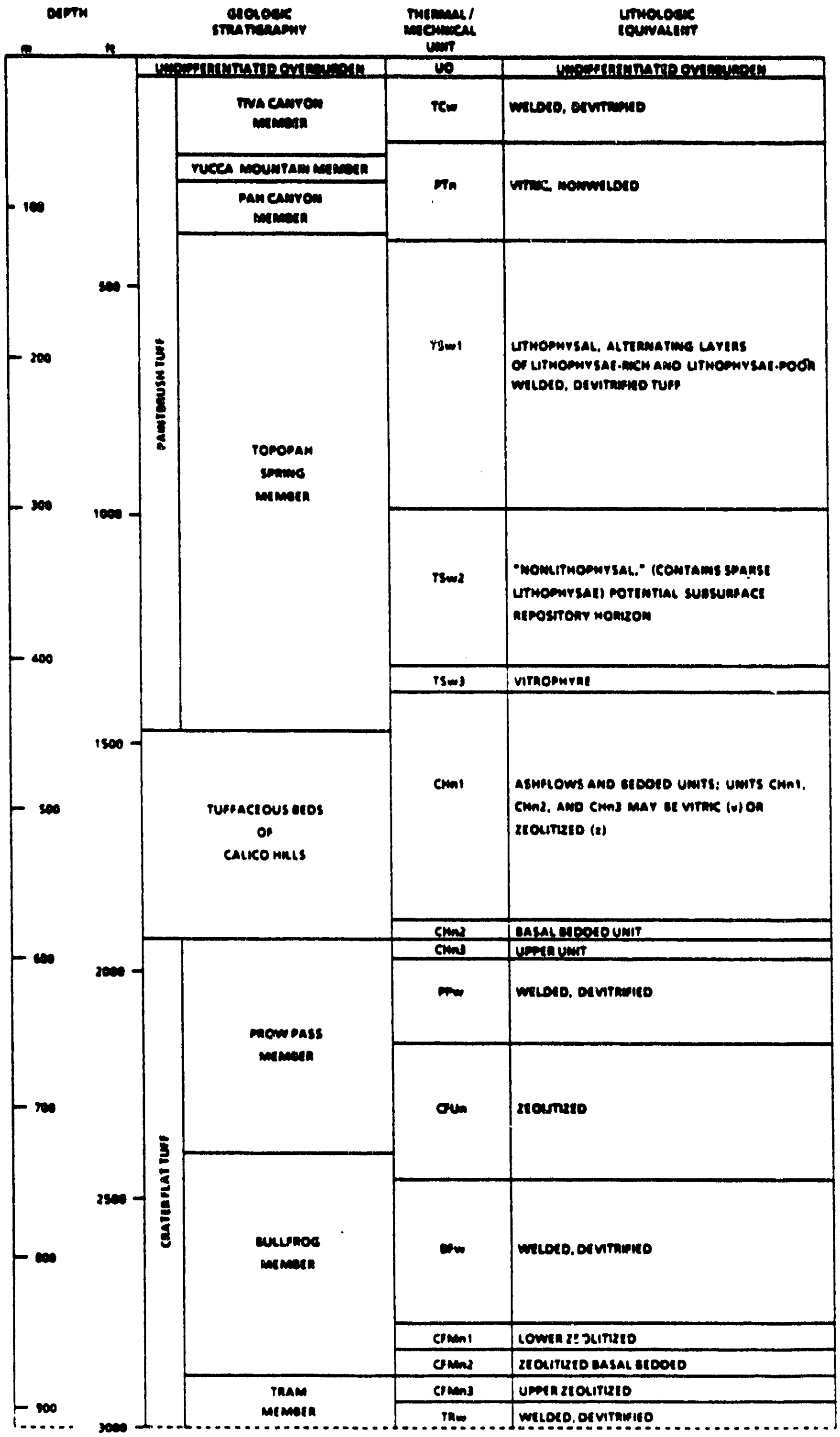


Figure 2. Lithologic and Thermomechanical Column of the ESF and Potential Repository Site

1.7.1 Tunnel Boring Machines

Tunnel boring machines (TBM) excavate circular openings by continuously thrusting and rotating a full-face cutterhead into the rock (Figure 3). The cutterhead is dressed with disk-shaped rolling cutters which penetrate and chip the rock under the thrusting action of the machine (Figures 4 and 5). The broken rock which falls to the tunnel invert is then picked up by buckets mounted on the periphery of the cutterhead. The buckets dump the cuttings into a centrally located chute that loads a conveyor for transport to the rear of the machine. There the cuttings are transferred to a gantry conveyor that is part of the backup unit. The gantry conveyor unloads the muck into rail cars or a conveyor system that moves the muck out of the tunnel to a shaft hoisting facility.

Cutterhead torque and rotation are provided by a set of electric motors mounted either directly behind the cutterhead or at the rear of the machine (Figure 6). Cutterhead thrust is provided by a set of grippers that push against the walls of the opening. Various types of gripping systems are available for different ground conditions and excavation requirements. Some machines use a single set of grippers coupled with a frontally mounted cutterhead shoe for additional stability and for steerablity during boring.

In bad ground conditions such as highly fractured, blocky, or squeezing rock, the tunnel boring machine usually is fitted with a full circular double telescoping shield to provide immediate roof support. Ring beams or precast concrete segments can be installed directly behind the machine shield with a mechanical erector. Some TBMs designed for bad ground use oversize grippers to reduce ground pressure and allow development of the necessary forces without failing the rock beneath the grippers. Other machines develop forward thrust by pushing against the liner segments already placed behind the shield.

Recent improvements and innovations in TBM technology have enabled their use in nearly all types of ground conditions, provided that the ground conditions are adequately characterized and understood. TBMs can be designed to excavate inclines or declines of varying grades. Inclines of up to 45° have been successfully completed with TBMs. The TBM productivity limitation in driving declines is the effectiveness of muck pickup from the invert and the limited ability of conveyors to transport muck upslope. Utilization percentages are adversely affected by the accumulation of muck at the heading. To date no TBM has driven a decline greater than about 17°.

TBMs also can be designed to negotiate various curve radii, to make turnouts from existing entries, or to bore through intersections. At present, efforts are underway to design TBMs with turning radii as low as 50 ft (15 m) for a 16 ft (4.9 m) diameter machine. Such designs also incorporate rotatable gripper assemblies so the machine can pass through existing mine intersections.

Conveyor belts, which create a truly continuous haulage system, are finding increasing use with TBMs. Such systems allow higher machine utilization and faster rates of advance compared to conventional rail transport

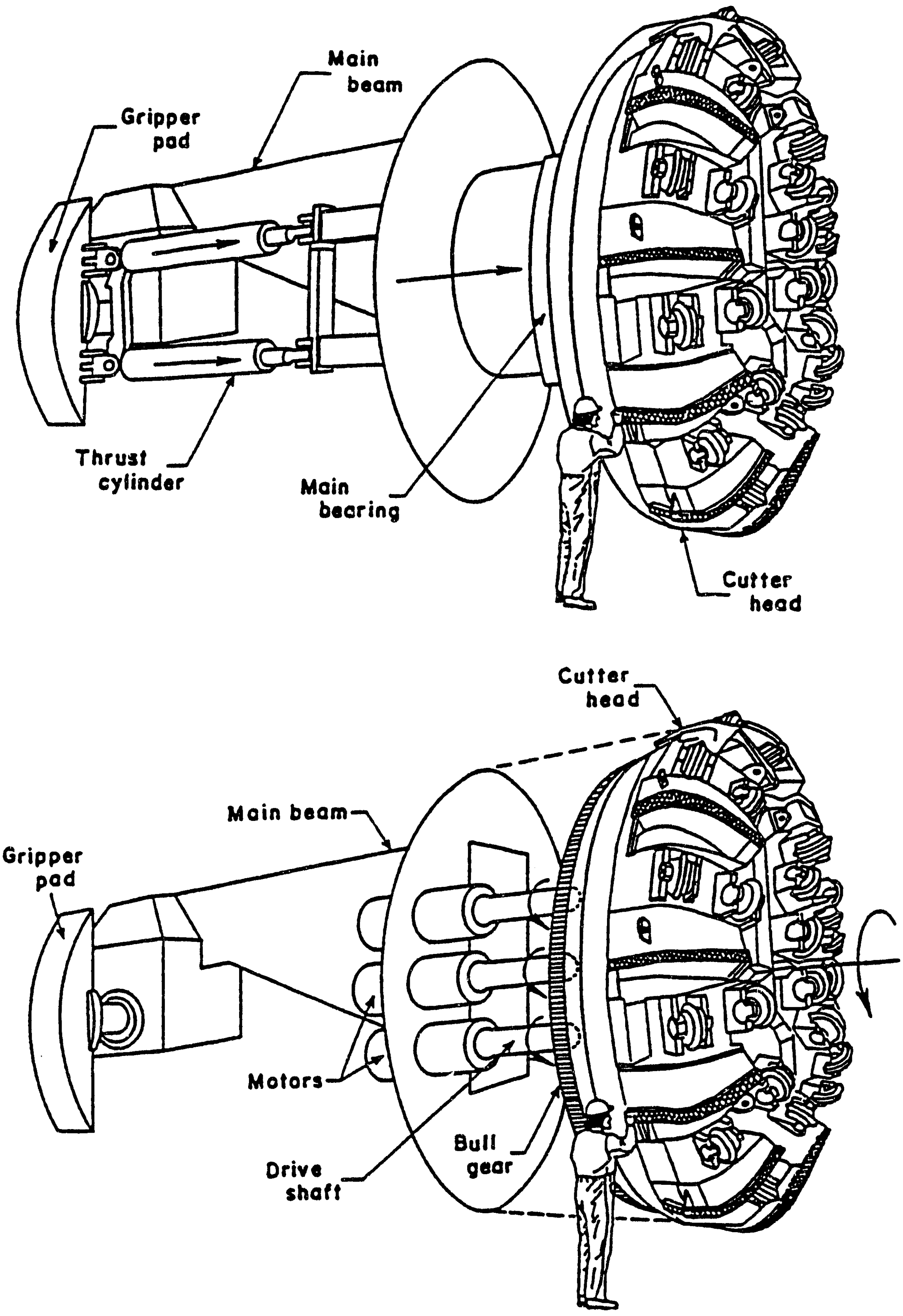


Figure 3. Schematic Drawing of Generic Thrust and Torque Systems of a Tunnel Boring Machine (TBM)

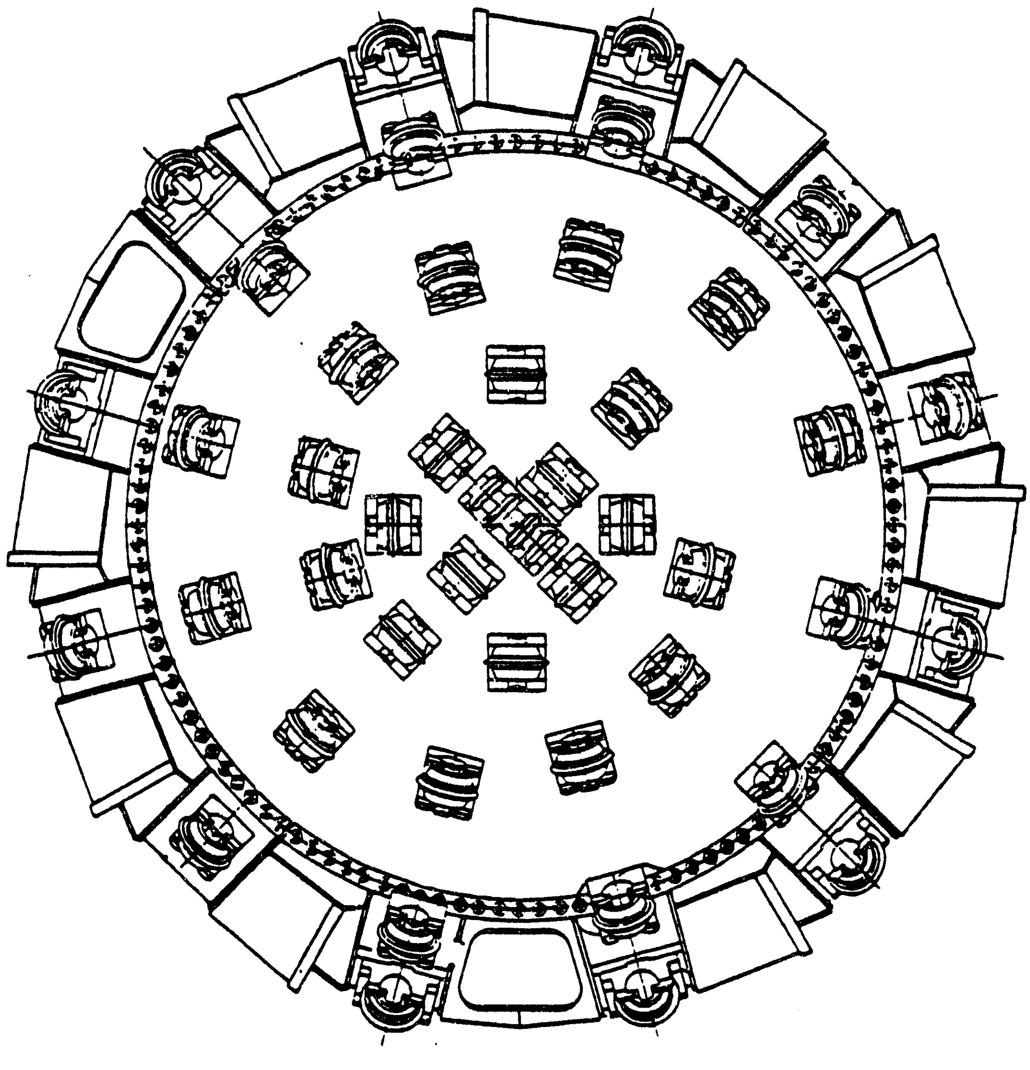


Figure 4. Head-on View of a TBM Cutterhead Mounted With Disk Cutters

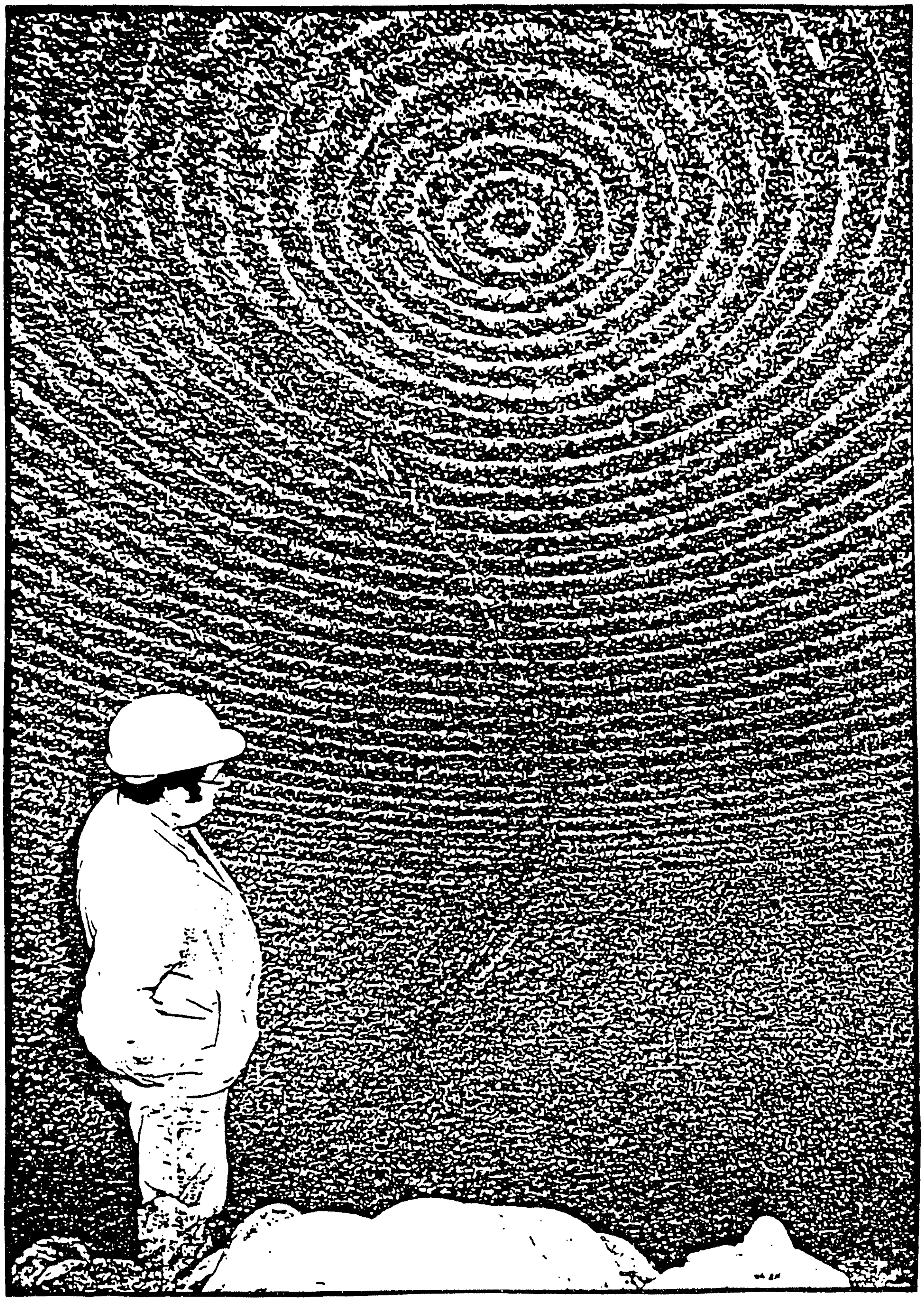
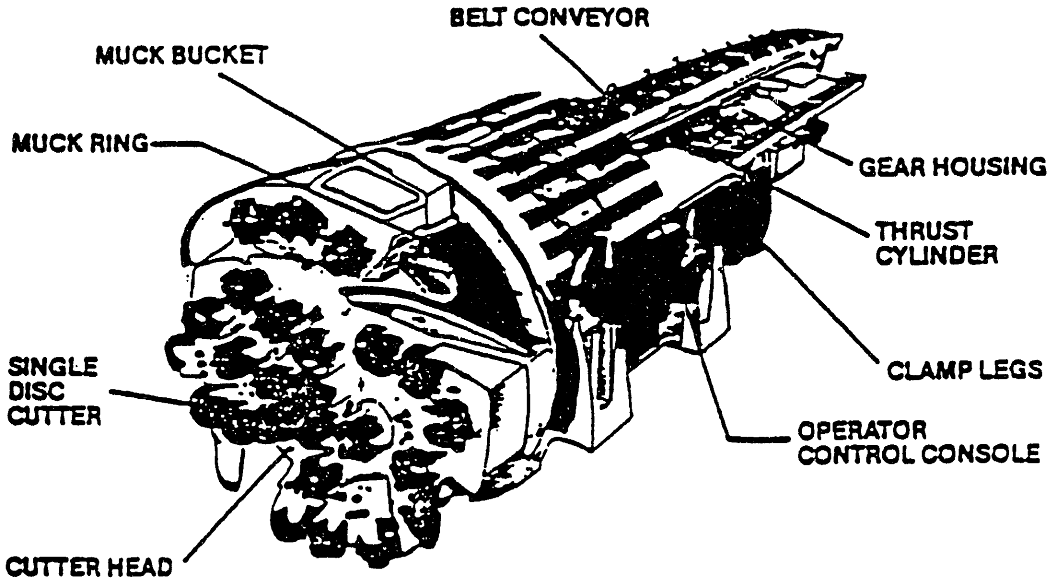
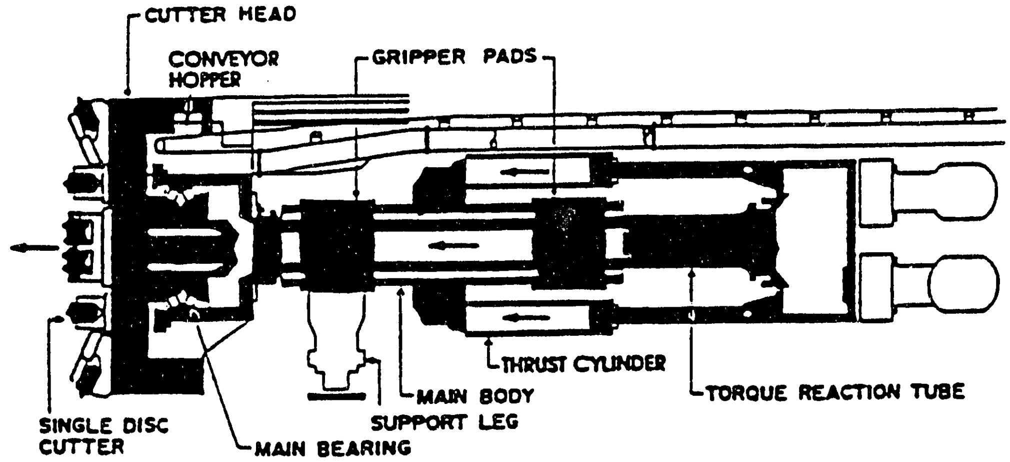
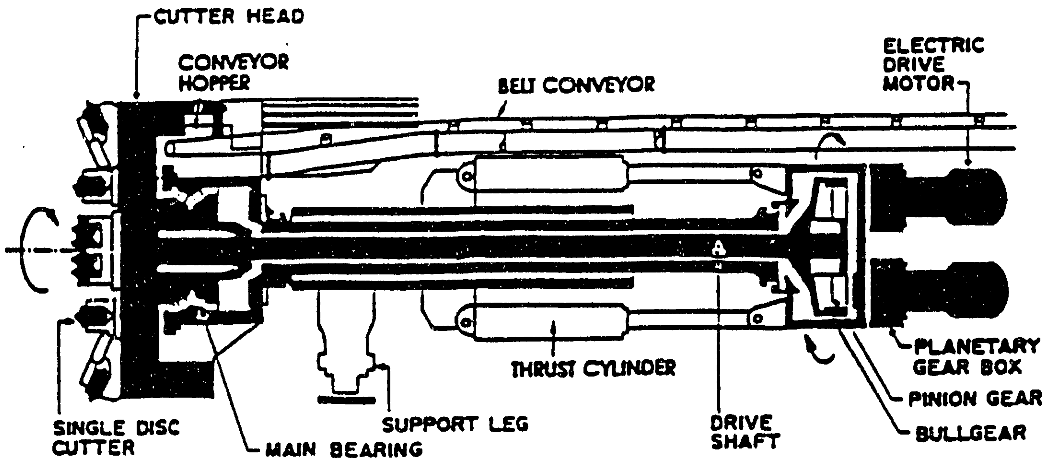


Figure 5. The Rock Face Left by a TBM. Note the circular cutter paths and the planar geologic feature on which the observer is standing.





Thrust System



Torque System

Figure 6. Schematic Drawing of a TBM Showing Various Systems

systems. Because of its continuous operation, the entire muck handling system can be automated, reducing labor requirements and increasing worker safety. However, this system combined with the full face design limits access to the face for mapping or other science studies.

1.7.2 The Mobile Miner

The Mobile Miner is a relatively new mechanical excavation concept developed primarily for mining applications. It is intended as a mobile hard rock mining machine that is flexible enough for both production and development work. To achieve the goal of flexibility, it is designed as a partial-face excavator (Figure 7). Its production rate thus is not intended to compete with TBM production rates where flexibility and mobility are not required. Both traits, however, are advantageous in mining. Additionally, the rectangular opening created by the Mobile Miner is more suited to most mining operations than the circular opening created by TBMs.

The Mobile Miner excavates the rock with a narrow vertically rotating wheel laced with peripherally mounted disk cutters (Figure 8). In operation, the wheel sweeps across the face from side to side as it rotates in a vertical plane, creating a rectangular opening with arched ribs and an arched face. The opening height is determined by the wheel diameter while the width is controlled by the width of the swing. An apron under the cutterwheel picks up the muck and transfers it to a conveyor for discharge in to the backup system. Cutting forces typically are provided by the mass of the machine, but gripper systems are used for additional thrust when needed. The machine is mounted on crawlers to increase mobility. The Mobile Miner typically is more flexible in application than TBMs, but cannot match the production rates of a full-face machine.

The Mobile Miner can excavate alcoves and rooms in addition to drifts. A new design variation includes a ranging wheel that modifies the basic arched rib into a horseshoe cross section. Other variations include double ranging drums to enlarge existing openings. Since the Mobile Miner is a partial-face machine, access to the face for support installation or geologic mapping is relatively easy during the excavation process.

1.7.3 Roadheaders

Roadheaders excavate rock with point attack cutters (also called picks or drag bits) mounted on the rotating end of a movable boom (Figure 9). The boom movements are controlled vertically and horizontally to vary the size and shape of the opening. The muck is collected by apron-mounted gathering arms and transported to the rear of the machine by a central chain conveyor.

Roadheaders excavate rock through either a milling or a ripping action, with the preferred design depending on the rock conditions and the rock abrasivity. Ripping machines employ a transverse cutting action. They transmit power from the cutter motor through a spiral bevel gear box to two cutterheads that rotate perpendicular to the machine axis. Milling machines transmit power from the cutter motor through an epicyclic gear box

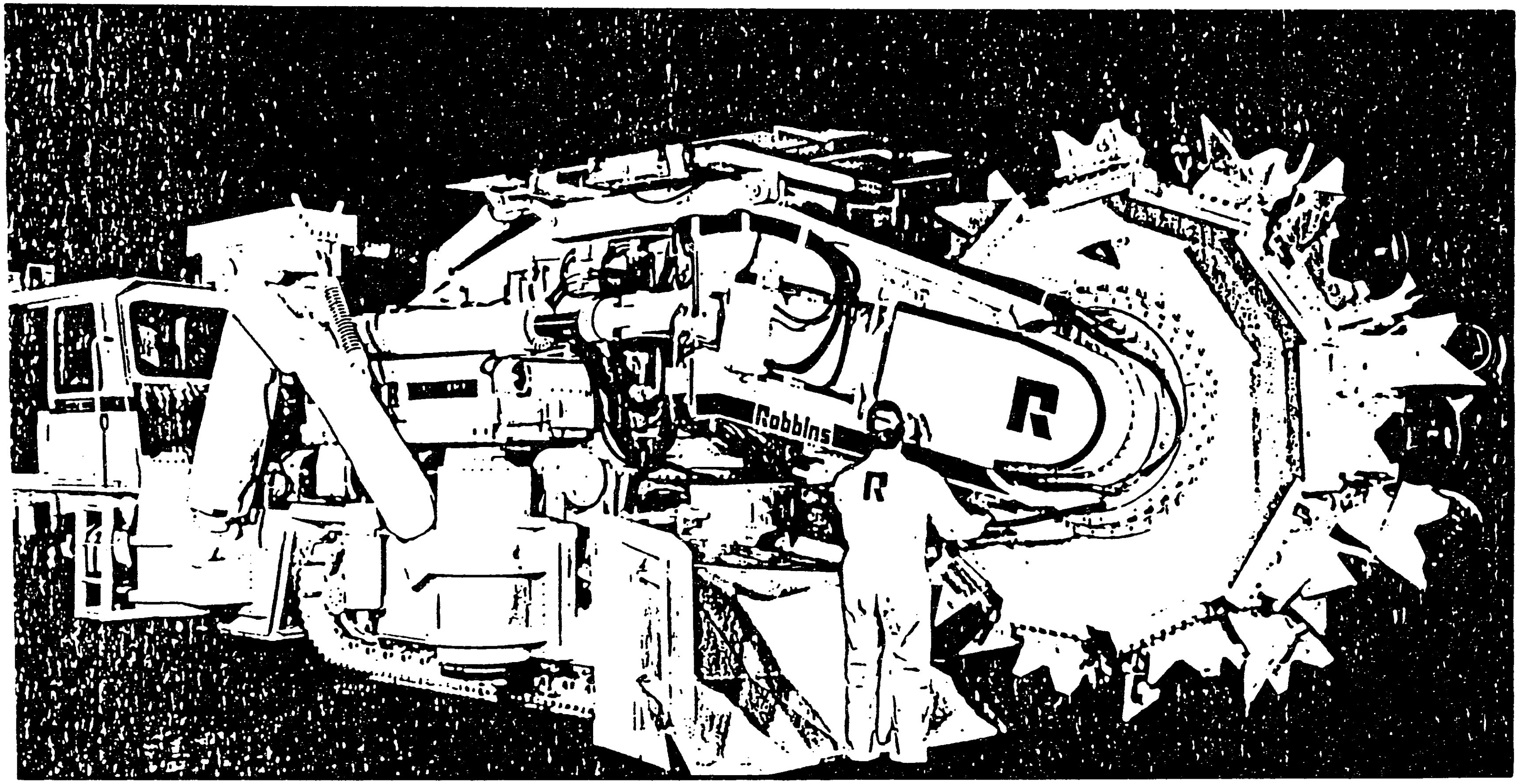


Figure 7. The Robbins Mobile Miner

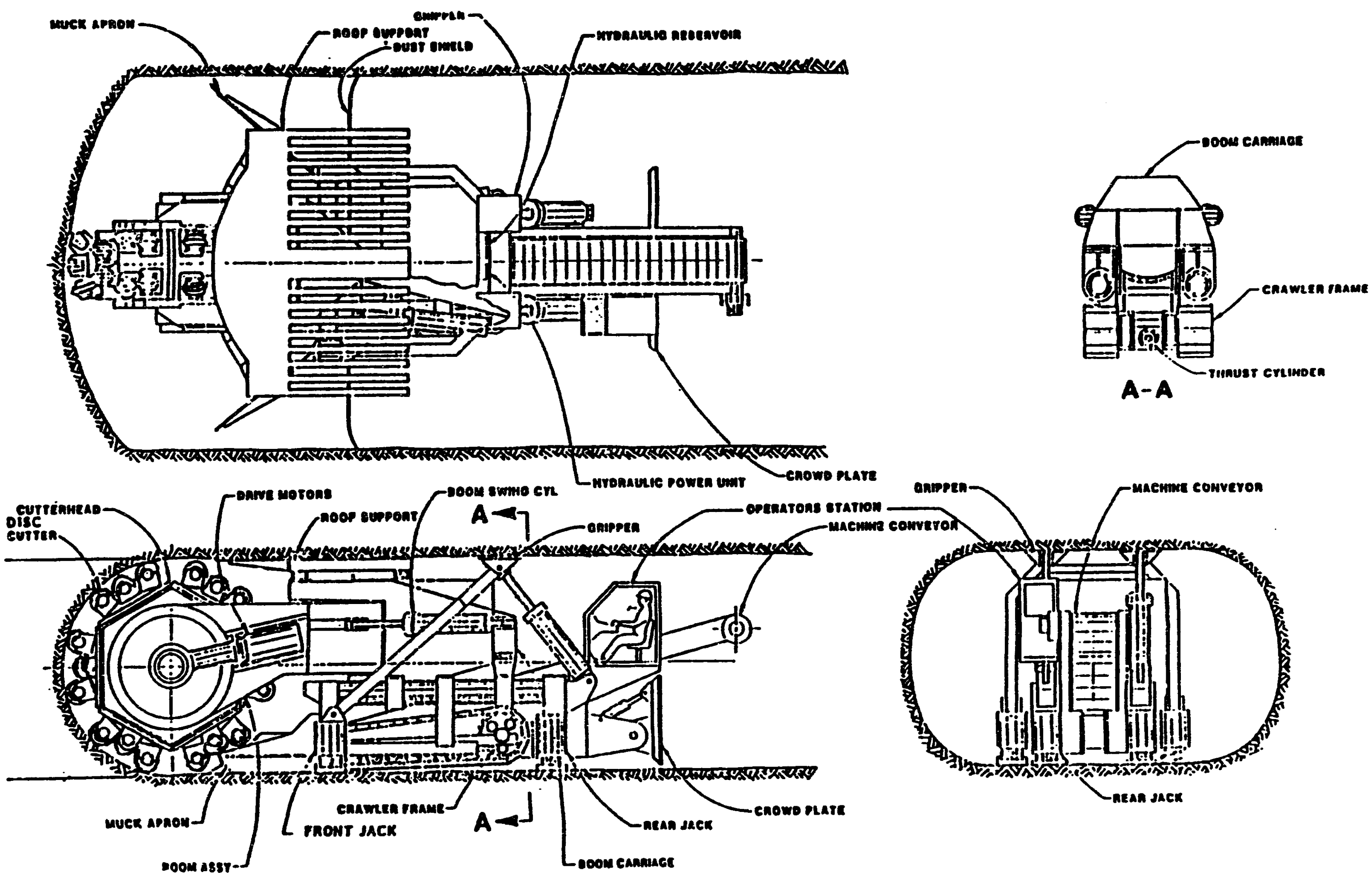


Figure 8. Schematic Views of the Mobile Miner in Operation

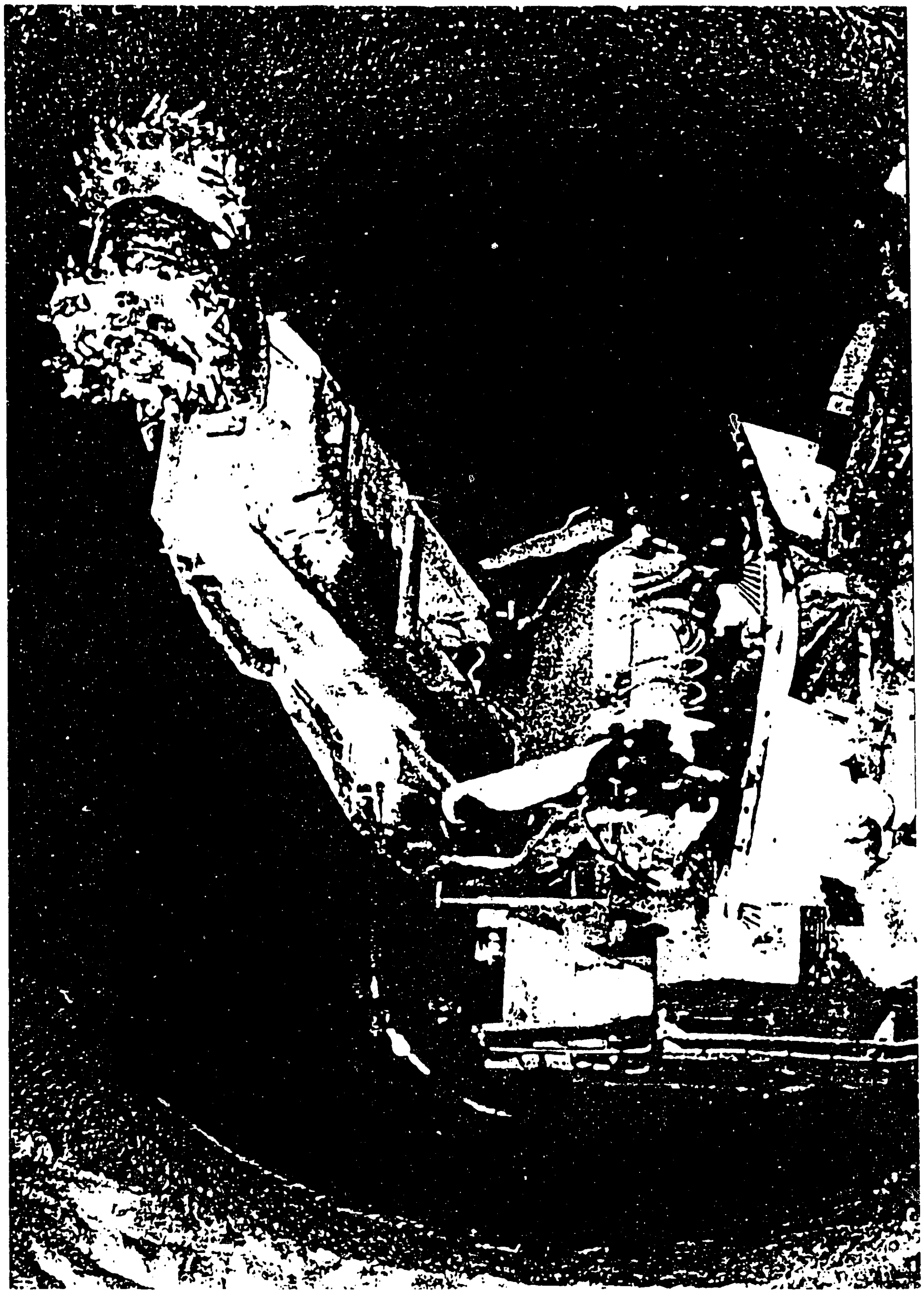


Figure 9. A Ripper-type Roadheader

to a single cutterhead that rotates in-line with the cutter boom. Ripper-type drums laced with conical drag bits generally are recommended for use in harder rocks.

Although roadheaders are flexible and versatile excavators, their use has generally been limited to rock whose uniaxial compressive strength does not exceed 15000 psi (103 MPa). Stronger formations can be broken if they contain a sufficiently dense fracture network so that the machine can rip blocks off the face. Also, being partial-face machines, roadheaders cannot match the production rates offered by full-face excavators such as TBMs. However, their high mobility and their ability to create openings of practically any shape and size makes them attractive for many rock excavation projects.

Recent developments in roadheader technology include heavier and stiffer machines with improved automatic guidance and profile control devices. Further, better understanding of bit-rock interaction has led to more efficient bit lacing patterns. These advances have improved machine performance and prolonged bit life. The power that can be delivered to the cutting boom also has increased substantially, enabling the machine to cut much harder rocks than was considered feasible only a few years ago. The main barrier to further improvements at present appears to be bit technology. Unless new bits capable of withstanding higher cutting loads while giving acceptable wear performance are developed, roadheaders probably will not find much use in hard rock format ions. A promising alternative seems to be the use of disk cutters in the place of drag bits. This would allow the machines to attack harder rocks; however, it remains to be seen whether the high thrusts required for efficient disk cutter operation can be generated effectively without sacrificing the mobility that is such an advantage of roadheaders.

After consideration of the maximum uniaxial compressive strength and estimated abrasivity of the tuffs, a heavy duty roadheader was selected for the analysis. Heavy duty machines are those which weigh in excess of 75 tons (68 mt) and carry 400 hp (300 kw) cutterhead motors. Standard-grade high-cobalt carbide bits designed for brittle rock and good muck clearance were chosen for lacing the cutting boom.

1.7.4 Blind Shaft Borer

Several options are available for the mechanical excavation of shafts (Figure 10). If underground access exists, a shaft can be raise-drilled or reamed from an initial pilot hole as illustrated in the figure. Without prior access to the underground, shafts have to be excavated blind using full- or partial-face machines with effective means of muck pickup and removal from the face. This also is shown in the figure. Additionally, roadheaders could work at the bottom of a shaft in an adaptation of the drill-and-blast technique of shaft sinking. Drilling of shafts from surface-mounted rigs is not considered in this report due to the need for considerable quantities of fluids to remove the cuttings. This would violate the requirement of minimal introduction of fluids into the rock mass during site characterization and ESF construction.

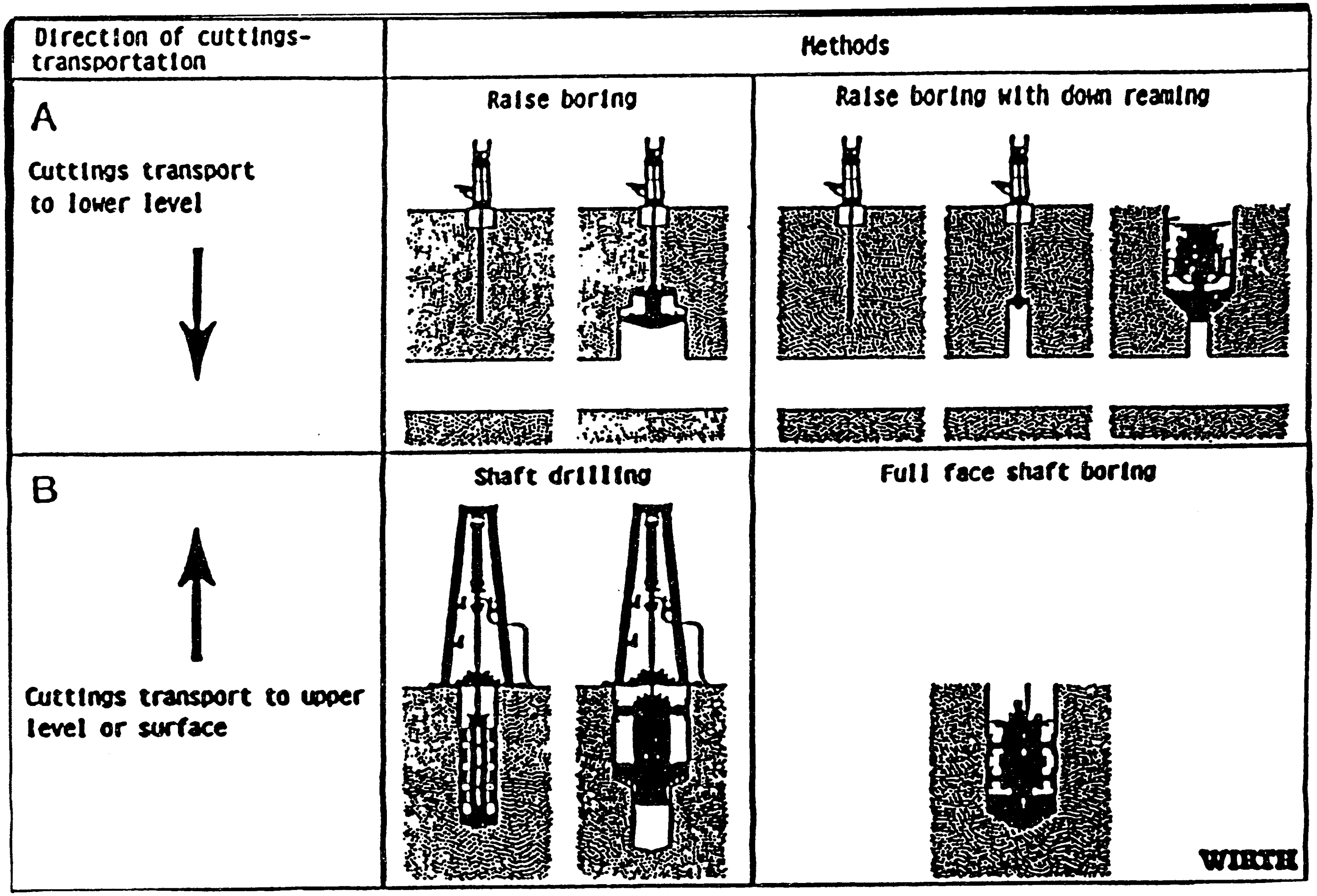


Figure 10. Various Methods of Shaft Drilling

The blind shaft borer (BSB), in its simplest definition, is a double-shield TBM turned on end (Figure 11). It operates very much like a TBM in terms of rock penetration and the design of the gripping system. The cutterhead design parameters are similar to those used for TBMs, with modifications for muck pickup against gravity from the bottom of the excavation. The achievable penetration rate is limited primarily by the support systems, especially muck removal and shaft lining.

1.7.5 Vertical Wheel Shaft Boring Machine

The vertical wheel shaft boring machine (SBM) (Figure 12) is a relatively new concept for the mechanical excavation of shafts in rock. The principles used to excavate rock are the same as those used in the Mobile Miner, where the rock is broken by a rotating, thin cutterwheel peripherally mounted with disk roller cutters. For shaft excavation, the cutterwheel assembly is rotated about the shaft axis and thrust is applied downward, in addition to the cutterwheel being rotated about its own horizontal axis. A bulldozer-type blade follows the cutterwheel and scrapes the cuttings into a pile. A clamshell bucket picks up the pile at intervals and loads it into a hoist for transport to the surface.

1.7.6 Raise Drills

Shafts also can be excavated by raise drilling if underground access such as a slope or a previously constructed shaft already exists. In such a situation, raise drilling is the fastest, least expensive, and safest way to construct a shaft. Raise drilling can be accomplished by upreaming or downreaming a pilot hole, or by blind boring upwards (boxhole boring) (Figures 10, 13, and 14). Raise drills also can be used to bore a large pilot hole for subsequent enlargement by a shaft reamer such as a V-Mole.

The deepest shafts constructed to date by raise drills were two of 16 ft (4.9 m) diameter bored from a depth of over 2000 ft (610 m) in an Alabama coal mine. They were built in 1979 using a Robbins model 81R. More recently, a 20 ft (6.1 m) diameter shaft was bored to a depth of 1000 ft (305 m) with an Ingersoll-Rand R-211 machine. Pulling a 16 ft (4.9 m) diameter shaft from a depth of about 1185 ft (360 m), as required in the preliminary designs, is well within the range of capabilities of the more powerful commercially available rigs.

1.7.7 The V-Mole

The V-Mole (Figures 10a and 15) excavates from the surface downward. It disposes of the rock cuttings through a large-diameter pilot hole previously created by a raise drill. Thus, underground access must already exist for the V-Mole to be considered for shaft construction. The pilot hole also is used for machine guidance. Steering corrections can be made during operation to maintain strict verticality of the shaft, an important requirement for future hoisting. The V-Mole is similar in principle to the BSB except that the muck is disposed of downward rather than being hoisted up.

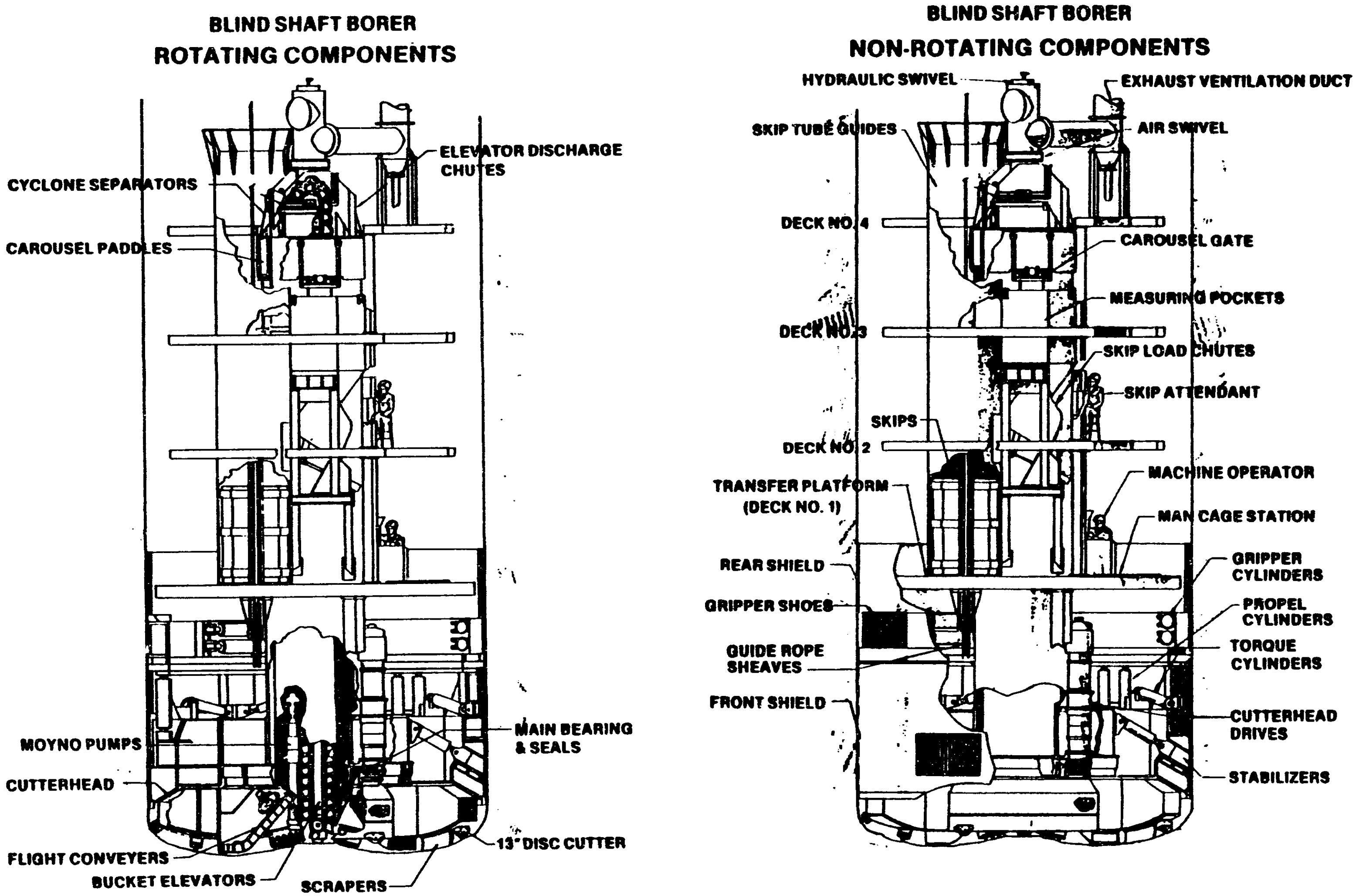


Figure 11. Schematic Drawing of the Rotating Components of a Blind Shaft Borer

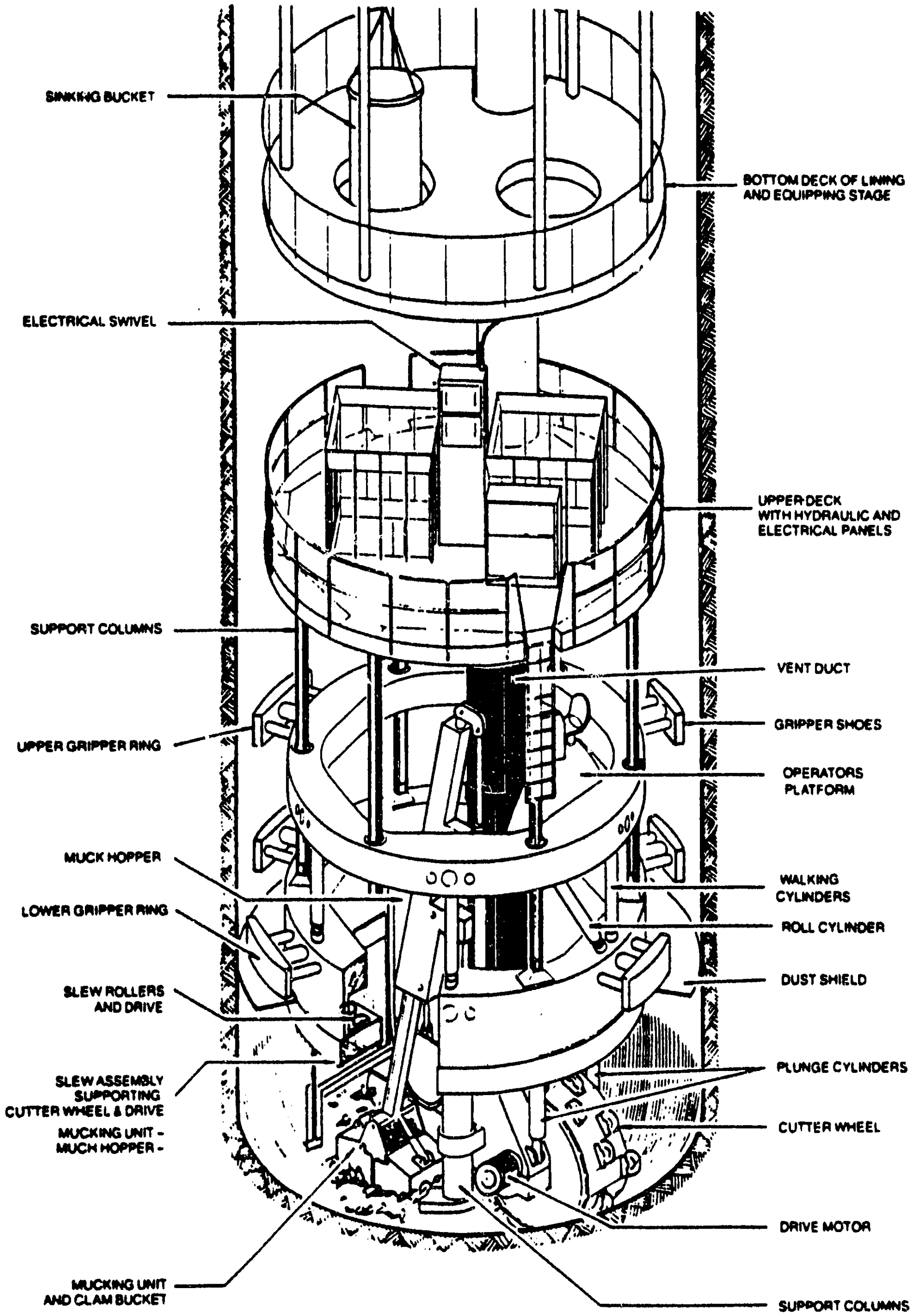


Figure 12. Schematic Drawing of a Vertical Wheel Shaft Boring Machine (SBM)

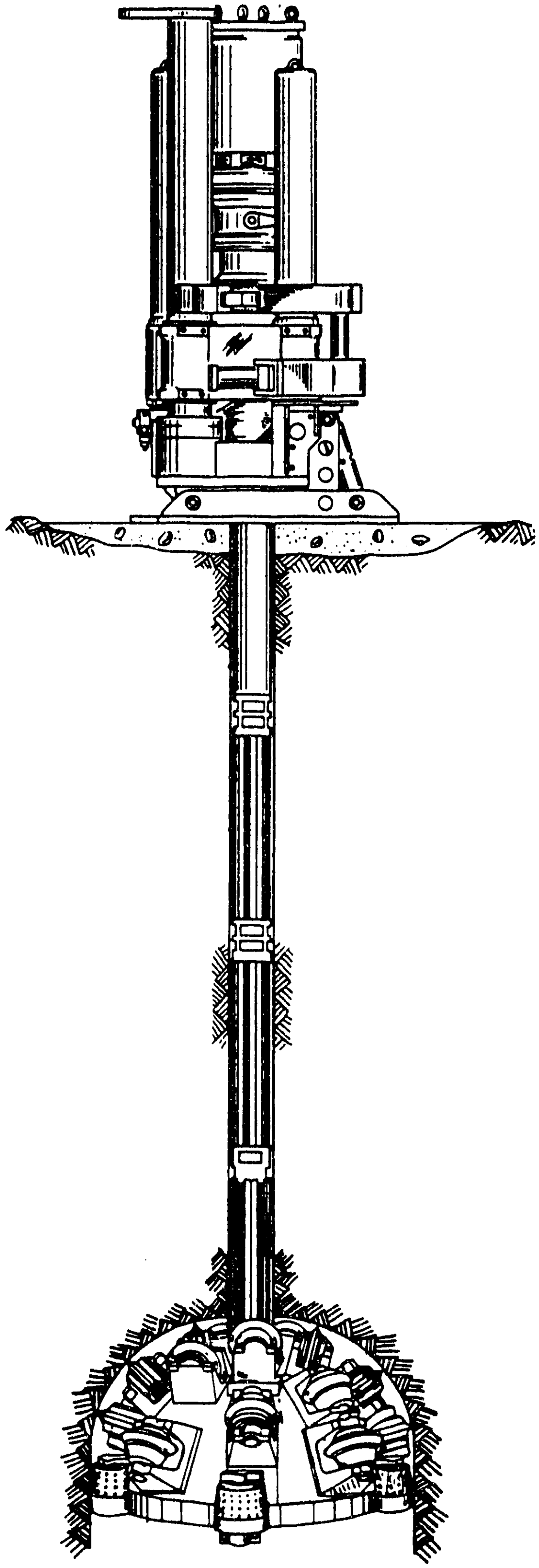


Figure 13. Schematic Drawing of a Raise Drill With a Domed Reamer Head

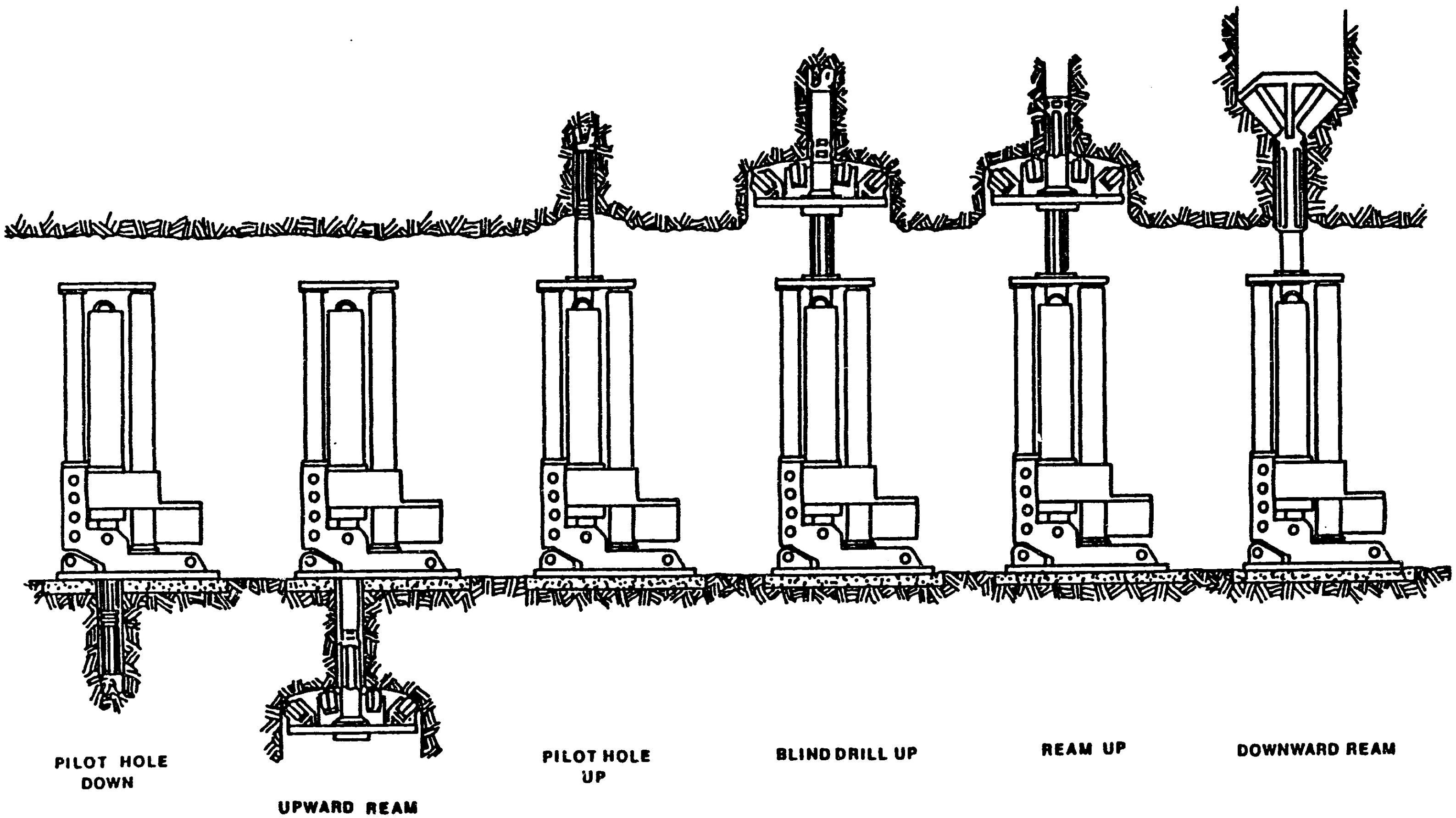


Figure 14. Various Modes of Operation of a Robbins Raise Drill

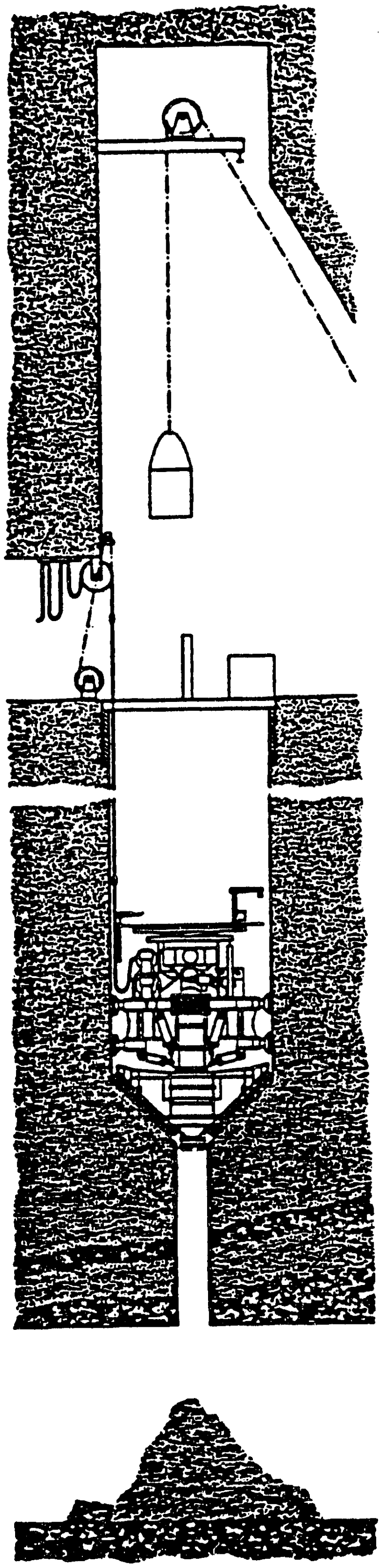


Figure 15. Schematic View of a V-Mole in Operation. Note the pre-existing pilot raise.

V-Moles have been used successfully to excavate shafts up to 23 ft (7.0 m) in diameter and the deepest being 1930 ft (590 m). Nine shafts of 16 ft (4.9 m) diameter have been bored with the V-Mole to depths of up to 1000 ft (300 m). Their advance rates averaged 20 ft/day (6.1 m/day), with the fastest reaching 44 ft/day (13.4 m/day). In recent years, a blind version of the V-Mole has been developed and tested in German coal mines. Both hydraulic and pneumatic muck removal systems have been tried with mixed success in this adaptation.

1.8 Excavation Requirements

Although the designs for the ESF at Yucca Mountain are not begun, several conceptual design descriptions in the Site Characterization Plan Conceptual Design Report (SCP/CDR) (MacDougall et al., 1987) and in the ongoing DOE ESF Alternatives Study were used as the baseline for the performance predictions calculated in this task. The descriptions found in these two sources were reviewed to determine the necessary parameters of each opening, which included:

- Diameter or size.
- Length of drift or depth of shaft.
- Slope or attitude.
- General layout of the openings relative to each other.

Assumptions had to be made regarding such important parameters as tunnel and shaft sizes and numbers of drifts, shafts, cutouts, rooms, and other excavations. The main assumptions are listed below:

1. For the Mobile Miner two drift sizes were assumed. Since the main intersect drifts had a cross-sectional area of 490 ft^2 (46 m^2) when excavated by TBM, a 30.5 ft wide by 16ft high (9.3 m by 4.9 m) opening was selected for the Mobile Miner to give a similar area. A 22 ft wide by 14 ft high (6.7 m by 4.3 m) opening was assumed for the main test area.

2. All ramps (with one exception) were modeled as declines.

3. All the main drifts were essentially horizontal; i.e., with slopes less than 1.5°.

Based on the above discussion and assumptions, the following excavation and machine dimensions were used in the performance analyses presented here:

1. Tunnels (drifts) of various cross-sectional areas and shapes.

   a. Tunnel boring machine - circular drifts 25 ft (7.6 m) in diameter. Two machines, one a standard configuration and the other a high power configuration, were evaluated. Both were hard rock, open gripper type TBMs.

b. Mobile Miner - rectangular drifts 14 ft by 22 ft (4.3 m by 6.7 m)and 16 ft by 30.5 ft (4.9 m by 9.3 m).

c. Roadheader - horseshoe-shaped drifts 22 ft wide by 12.5 ft high (6.7 m by 3.8 m) and 15 ft wide by 21.5 ft high (4.6 m by 6.6m).

2. Vertical shafts of 16 ft (4.9 m) diameter after lining.

a. Shaft boring machine - 18 ft (4.9 m) diameter, vertical wheel, partial face type.

b. Blind shaft borer - 18 ft (4.9 m) diameter, full face type. Performance was calculated for two speeds of operation.

c. Raise drill - 18 ft (4.9 m) diameter.

d. Raise drill - 6 ft (1.8 m) diameter, to drill a pilot hole for the V-Mole.

e. V-Mole - 18 ft (4.9 m) diameter, shaft reamer. A currently available model and an upgraded version were evaluated.

1.9 Prediction Methodology

Performance prediction methods for mechanical excavators are founded on basic principles, empirical methods, and professional engineering judgment. The state of the art has not advanced to the point where predictions based on rock properties can rigorously follow from basic considerations. The problem stems from the variability and complexity of the rock response to mechanical cutting. Rock properties vary spatially to the extent that significant differences in cutability can occur in a single excavation. The response of the rock to mechanical cutting action is very complex and involves several failure modes: chip formation, crushing, and crack formation.

The prediction methodology usually focuses on the action of an individual cutter on the rock and then is generalized to the action of the entire machine and its backup system. Some alternate methods reverse the process: they calculate global load on the excavator and back-calculate forces on individual cutters.

Since cutter load is not measured when predicting performance on the basis solely of rock physical properties, indirect means of predicting cutter load from those properties are required. Experience with cutter-rock interactions has led to empirical relationships between certain rock properties and cutter load. The most crucial rock properties for this purpose are the uniaxial compressive strength (UCS) and the shear strength. RQD and tensile strength also play important roles in some formulations.

The manners in which these properties are applied to machine performance prediction depends on the machine being considered. Different machines use different types of cutters, in different arrangements and on different frames. The following two sections (1.9.1 and 1.9.2) outline the procedures used with the two basic types of cutters: disk cutters and point attack cutters. The equations estimate, first, cutter forces, using rock properties and machine parameters, then they estimate machine performance.

The remaining sections (1.9.3 through 1.9.6) discuss how these generic procedures are applied to the types of excavators considered in this report.

1.9.1 Disk Cutters

Disk cutters are found on TBMs, the Mobile Miner, the BSB, and the V-Mole. The prediction methods for these machines are similar. Ozdemir et al. (1973, 1977, and 1979) demonstrated a relationship of disk cutter performance to rock properties, cutter shape, and machine operating parameters, including cutting geometry. The normal force on a single disk cutter is determined by:

$$f_n = D^{1/2}P^{3/2}(4(UCS)/3 + 2T(S/P - 2\tan a/2))\tan a/2 \quad [lbf] \qquad (1\text{-}1)$$

The rolling force on the cutter is:

$$f_r = f_n \tan b \quad [lbf] \qquad (1\text{-}2)$$

Where:

f_n = normal force
f_r = rolling force Rock properties:

Rock properties:

UCS = uniaxial compressive strength (psi)
T = shear strength (psi) Cutter shape:

Cutter shape:

D = cutter diameter (in.)
a = cutter edge angle (deg) Cutting geometry:

Cutting geometry:

S = spacing (in.)
P = penetration (in.)
b = the angle of the center of force on the cutter, a function of penetration and cutter diameter (deg).

From these relationships, forces on each cutter as a function of penetration are established for a combination of rock and machine. Physical properties measurements of the rock fix the compressive and shear strengths. Selection of the machine fixes cutter diameter, edge angle, and spacing. Professional engineering experience establishes the allowable forces that a particular machine can withstand and determines the penetration of the machine based on those forces. Once the penetration and the cutter forces are established, the mechanical excavator operating characteristics are calculated. Total machine thrust is the sum of the normal forces acting on each cutter:

$$\text{Thrust} = f_{n1} + f_{n2} + \ldots + f_{nk} \quad [\text{lbf}] \tag{1-3}$$

where:

k = number of cutters.

Similarly, total machine torque is the sum of the rolling forces on each cutter multiplied by the moment for that cutter:

$$\text{Torque} = (f_{r1})(m_1) + \ldots + (f_{rk})(m_k) \quad [\text{ft-lbf}] \tag{1-4}$$

where:

m = moment on cutter i

The instantaneous penetration rate (expressed in feet per hour) is determined by the machine cutterhead rotational rate and the penetration. If the cutter can penetrate the rock a known distance, then the penetration of the entire machine becomes that known distance per revolution of the cutterhead. In this manner, each cutter maintains that constant known penetration distance while the cutterhead is rotating.

Expressed in feet per day, the advance rate modifies the penetration rate with the utilization factor:

$$\text{Advance Rate} = (\text{penetration rate})(\text{utilization}) \quad [\text{ft/hr}] \tag{1-5}$$

where:

$0 <= \text{utilization} => 1$

Determining the utilization factor requires engineering judgement of many factors. These factors are discussed in Section 2.

Cutter costs largely are a function of rock abrasivity. Application of abrasivity measurements to cutter costs requires a large database of empirical performance data. For example, Cerchar abrasivity is an index and is not related to basic principles. Consequently, predicting cutter costs is based on experience.

From the above discussion, it can be seen that the prediction process is by necessity iterative. Cutter forces are a function of penetration, spacing, cutter diameter, and cutter edge angle after rock properties have been fixed. The first choice of machine layout is almost always not adequate. The cutting variables will go through many changes before a workable design arrangement is determined. Further, not all designs are geometrically possible as the cutters must physically fit on the cutterhead without mutual interference. Professional experience in machine design is required to complete the performance prediction process.

It can be seen also that there are many ways to iterate the above relationships to predict excavator performance. The starting point for the process is determined by professional judgment.

1.9.2 Point Attack Cutters

Predicting the performance of point attack cutter excavating machines is more judgmental than for disk cutter machines. The present state of the art is such that the prediction process depends on sets of empirical databases rather than basic relationships of the cutting parameters. The roadheader performance prediction methodology employed in this report has been outlined by Neil and Taylor (1991).

In the methodology, the factors needed for performance prediction are:

SE = specific energy of cutting rock
hp = machine power (hp)
RQD = rock quality designation (%)
UCS = uniaxial compressive strength (psi)
t = tensile strength (psi)
Abrasivity = Cerchar abrasivity index (CAI)

The key parameters for prediction are the specific energy for cutting and the excavation machine power. Specific energy is the energy needed to excavate a unit volume of rock. By dividing machine power by specific energy, the volume of rock a machine can excavate per unit time is determined. This is the instantaneous penetration rate of the cutterhead into the rock:

$$\text{Penetration rate} = (EF)(hp)/(SE)\ [yd^3/hr] \qquad (1\text{-}6)$$

Where:

hp = machine power (hp)
SE = specific energy ($hp\text{-}hr/yd^3$)
EF = machine efficiency factor

The specific energy is selected by consulting various databases of roadheader performance in similar rock types. Usually several rock types are compared and differences in cutability are noted.

Unlike TBM prediction, the penetration rate for the roadheader is calculated directly for the entire machine. Instead of calculating the load on one disk cutter and deriving the resultant load on the entire machine, the load on the entire machine is calculated first and the resultant load on the individual point attack cutters is derived afterward. Note that either penetration rate or machine power may be considered the independent variable depending on the requirements of the project or the limitations of the available machines.

By specifying the machine power, a minimum size machine is required. Machine from various manufactures that meet or exceed the minimum power requirement are then identified. Their operational and performance details

are studied to determine the appropriateness of the design to the task. Of particular interest are the penetration, cutterhead rotational speed, and sumping depth. These parameters refine the advance rate by accounting for the effect of using a partial face excavator. The final equation is:

$$\text{Advance rate} = (P)(R)(SD)(f)(EF)(k) \,/\, \{A/(D)(f)\} \quad [\text{ft/hr}] \qquad (1\text{-}7)$$

Where:

- P = penetration (in.)
- R = cutterhead rotational speed (rpm)
- SD = sumping depth (ft)
- f = cutting factor
- A = area of drift (ft^2)
- D = diameter of cutterhead (ft)
- k = constant (unit conversion)

Note: The cutting factor (f) is based qualitatively on RQD and the UCS/t ratio. As RQD and the UCS/t ratio increase, f decreases. The cutting factor ranges from 0.25 to 1.0; values around 0.75 were used in this study. See Neil and Taylor (1991) for further discussion.

Other design details are checked to verify machine suitability. Will the cutters overheat at the required operational parameters and rock types? Are cutters available at the required strength and expected life? Is the machine sufficiently massive and stiff?

Utilization is determined by the same process as for disk cutters. The advance per day then is determined. Cutter costs are determined by databases of costs in rocks with similar abrasivity and silica content.

As with disk cutters, performance prediction of point attack cutters is an iterative process. Iterations are performed during each step and between steps. As this brief outline shows, the process is highly judgmental. Experienced professional judgement is needed to estimate the various factors used.

1.9.3 Tunnel Boring Machines

EMI developed a comprehensive computer model of TBM operations for a previous client. This proprietary code follows the logic and the design steps that an experienced engineer employs in designing a tunneling machine for a particular project, as described in Section 1.9.1. First the code determines the optimum cutter size and geometry, cutterhead shape, and cutter layout based on rock characteristics. This is an iterative process. At each iteration the model checks for complete balancing of the cutterhead forces and interference between cutter housings, then calculates the expected performance in the specified rock type. The code determines the optimum thrust, torque, and power requirements along with the estimated penetration rate. It further determines the forces on individual cutters to assure none are overloaded according to the manufacturer's recommended bearing capacities. The final cutterhead design then is displayed on the computer screen in perspective drawings.

On a broader scale, the model has the capability to divide the entire project into segments according to tunnel length, size, grade, excavator type, and ground conditions. The cutterhead design is optimized for the segment with the most difficult ground conditions, all other parameters remaining equal. In addition, the code calculates project costs, including labor, overhead, and ground support. This code has been validated at EMI with several cases of field data.

1.9.4 The Mobile Miner

The performance of the Mobile Miner was estimated using proprietary computer modeling codes previously developed by EMI and the Robbins Co. The code algorithms are based on empirical relationships among cutter wear, rock toughness, and rock abrasivity, as well as rock strength. These codes have been validated with data from several sources, including field trials at the Mt. Index rock quarry in Washington (basalt and andesite)and actual machine use at Mt. Isa mines, Australia (norite and granite).

The Mobile Miner is a partial face machine and requires calculations similar to those discussed in Section 1.9.1 to determine machine advance rate.

1.9.5 Roadheaders

The theoretical cutting performance of a heavy duty roadheader was estimated with manual calculations from the unconfined compressive strength-specific energy curves for the rock types in question and from the specific energy-production curve of the chosen type of roadheader (see Section 1.9.2). Specific energy is a measure of the energy required to break a unit volume of rock. A given machine will have a characteristic specific energy versus production curve. The specific energy required for excavation of a given rock type and strength therefore in turn dictates the cutting performance of the roadheader.

1.9.6 Shaft and Raise Borers

The performance of the shaft boring and raise drilling machines was estimated using proprietary computer modeling codes developed previously by EMI and the Robbins Co. The BSB and the V-Mole use disk cutters, so the prediction methodology follows that described in Section 1.9.1. Raise borers use point attack cutters (Section 1.9.2).

Additional calculations were performed manually, particularly in the case of new conceptual designs such as the vertical wheel SBM. As this is a partial face disk cutter machine, the cutterhead was modeled as discussed in the disk cutter methodology presented in Section 1.9.1. The instantaneous advance was calculated and then the effect of the partial face added to determine actual advance, as in Section 1.9.2.

2.0 PERFORMANCE RESULTS IN THE POTENTIAL REPOSITORY HORIZON

As noted earlier, the primary objective of the Task 1.1 effort was to develop estimates of machine performance in the potential repository horizon material, as well as in other lithologic units likely to be encountered in various phases of site characterization and ESF construction. Performance prediction results for the potential repository horizon are discussed in this Section; results for the other tuff units are discussed in Section 3.

The performance of a mechanical excavator is best described by the achievable rate of penetration, the rate of advance, and the cutter costs. Normally estimates of these parameters would then be used as input to estimates of the overall project schedule and costs.

The penetration rate is the distance the machine actually bores into the rock per unit time that the machine is in operation. Penetration rate is expressed in units of feet per hour and is controlled by the design of the machine and the characteristics of the rock being excavated.

The rate of advance is the length of excavation created per unit of elapsed time, expressed as feet per 24 hour day. The advance rate was calculated from the penetration rate by multiplying it by an estimate of machine utilization (see Section 2.1), the fraction of elapsed time during which the machine is actually breaking rock. As might be expected, utilization figures depend on a multitude of factors and vary widely from project to project, even from location to location within a project. Utilization is a function of the entire excavation system, including not only mechanical aspects but also such social issues as management, scheduling, unions, personnel training, and any activities that interfere with the boring operation, such as mapping, experiments, and quality assurance. In general, machine utilization is low in the early phases. As personnel become more familiar with the rock and the machinery, the utilization factor usually improves, reaching its highest value in later phases of the project.

Cutter costs are the material costs of replacing cutters as they wear out during the excavation process. These costs usually are expressed in terms of dollars per cubic yard of rock excavated.

Since the ESF construction environment will be unique, the instantaneous cutting rates (yd^3/hr) and the related instantaneous penetration rates (ft/hr) are reported here along with the advance rates (ft/day). Utilization factors for a project such as the ESF almost certainly would be significantly different (lower) than the utilization factors used in the mining and construction industries. However, in the interest of completeness, utilization factors have been estimated in order to project overall advance rates.

2.1 Tunnel Boring Machines

Performance predictions were made for 25 ft (7.6 m) diameter standard and high power TBMs. The standard machine was equipped with 17 in. (43 cm) diameter disk cutters each rated at 50000 lbf (0.222 MN) average load. The high power TBM used the newly developed 19 in. (48 cm) diameter disk cutters with load ratings of 65000 lbf (0.289 MN). In addition, the high power TBM was able to rotate at 7 rpm rather than the 6.36 rpm possible with the standard configuration.

Table 2 lists the results of the performance estimates, along with important machine parameters. As might be expected, the high power TBM delivered a higher instantaneous cutting rate at a lower cutter cost, although more torque was required. The higher penetration rate was due to the greater allowable cutter loads and the faster rotational speed of the cutterhead. Cutter costs were lower because of the larger diameter cutters and the higher penetration rate.

Table 2

Performance Prediction of Two TBM Configurations in Average Physical Property Values For the Potential Repository Horizon (TSw2)

PARAMETER	STANDARD TBM	HIGH POWER TBM
cutterhead diameter (ft)	25	25
rotational speed (rpm)	6.36	7.0
cutters (# @ diameter (in.))	50 @ 17	47 @ 19
max cutter load (lbf)	50,000	65,000
cutterhead power (# motors @ hp)	6 @ 400	7 @ 450
max operating torque (ft-lbf)	1,982,000	2,026,000
operating thrust (lbf)	2,500,000	2,820,000
penetration per revolution (in)	0.18	0.25
penetration rate (ft/hr)	5.72	8.75
cutter life (hrs)	66	73
tunnel length per cutter (ft)	376	637
approx cutter costs ($/yd^3)	5.41	5.15

Estimating the daily advance rate required estimation of an average utilization factor for the TBM. The following factors influence machine utilization:

1. Tunnel grade.
2. Haulage method (rail, rubber-tired, or conveyor).

3. **Water inflow rate.**

4. **Rock quality.**

5. **Tunnel curves.**

6. **Crew training and motivation.**

7. Other: testing, characterization, wall mapping, etc.

As discussed earlier, the rate of advance was simply the product of the penetration rate and the utilization factor.

Estimating the overall advance rate is a judgmental process that was best achieved by breaking the project down into several tunneling scenarios based on the factors discussed below and outlined in Table 3. Each scenario illustrates a condition that may be encountered in construction and presents an excavator designed to effectively operate in the scenario. Separate utilization percentages and advance rates were determined for each segment.

Table 3 lists suggested haulage systems in addition to the expected utilization factors and advance rates for each individual scenario. The data shown here represent good commercial practice with a new machine/ backup system under steady state conditions. No significant delays due to rock support requirements were included. A widely spaced pattern of rock bolts was assumed to be adequate in the immediate vicinity of the TBM; more elaborate supports could be installed by the backup system with little effect on TBM performance.

2.1.1 Slope and Haulage System

The slope (grade) of the tunnel being driven affects TBM utilization and therefore the advance rate. A slight upgrade is the most favorable because inflowing water drains by gravity and haulage vehicles travel downhill when loaded. Slopes up to about +3° and down to -1° can be handled effectively by rail haulage systems. Thus, all excavations with design grades outside these limits must use some haulage/supply system other than rail, such as cog or hoist railways, conveyor belts, or trackless haulage (rubber-tired loaders and trucks). Slurry or pneumatic transport of muck also is possible, but neither has been proven cost-effective in a construction job.

When operating at its design penetration rate, the high power TBM produced approximately 310 tons (280 mt) of muck per hour. This cuttings volume virtually eliminated all of the haulage options except the conveyor. Neither cog nor hoist railways have the capacity to handle this volume of muck on a sustained basis. Trackless haulage also would be outpaced, requiring for example a ten ton truck to be filled every two minutes. Such a large number of trucks would create ventilation and traffic safety problems, particularly as the excavation lengthened.

Table 3

Projected Advance Rates of the Standard and High Power TBM Configurations in the Potential Repository Horizon (TSw2). Each scenario illustrates a condition likely to be found in ESF construction. (See Figures 18 and 20 for graphical comparison to other machines.)

STANDARD TBM:

scenario number	slope %	curve radius (ft)	backup system	penetration rate (ft/hr)	utiliz. %	advance rate (ft/day)
1	-1 to +3	none	rail	5.7	55	75
2	-1 to +3	none	conveyor	5.7	50	68
3	-8.9	none	conveyor	4.7	45	51
4	-14	none	conveyor	4.2	40	40
5	-21	none	conveyor	4.0	35	34
6	-1 to +3	600	rail	3.5	35	29
7	-8.9 to -21	600	conveyor	3.2	30	23

HIGH POWER TBM:

scenario number	slope %	curve radius (ft)	backup system	penetration rate (ft/hr)	utiliz. %	advance rate (ft/day)
1	-1 to +3	none	rail	8.8	55	116
2	-1 to +3	none	conveyor	8.8	50	106
3	-8.9	none	conveyor	7.5	45	81
4	-14	none	conveyor	7.0	40	67
5	-21	none	conveyor	6.8	35	57
6	-1 to +3	600	rail	5.0	35	42
7	-8.9 to -21	600	conveyor	5.0	30	36

Conveyor haulage systems are rapidly gaining popularity as they are now achieving utilization factors equal to those given by rail haulage. Before recent increases in their reliability, conveyor systems working with TBMs reached utilizations of slightly more than 30%. As improvements continue, conveyors probably will become the primary means of material haulage in mechanically bored tunnels. The fundamental advantage of conveyors is their truly continuous nature, which is very conducive to full automation.

2.1.2 Water Inflow

Generally, water inflows must exceed 1000 gpm (3800 l/min) to cause significant delays during tunnel excavation with TBMs. Flows of this magnitude are not expected to be encountered during construction of the ESF openings.

2.1.3 Rock Quality

The highest rates of TBM advance are associated with rock quality designation (RQD) values between 50% and 75%, which is the common range of the tuffs at the Yucca Mountain site (Langkopf and Gnirk, 1986). Very massive formations tend to reduce the penetration rate and increase the frequency of required cutter changes. At the other end of the spectrum, RQD below about 25% indicates poor ground conditions that cause frequent TBM halts for support installation or other ground treatment.

Present TBM technology has advanced to the point that the machines can be designed to accommodate bad ground conditions through the use of different types of shields combined with standard methods of ground support (concrete liner segments or ring beams, rock bolts, wire mesh, and shotcrete). Installation of nearly all types of rock support, however, reduces the utilization percentage of the excavation machine.

2.1.4 Curves

The excavation of curved tunnels adversely affects TBM advance rate because the machine thrust and penetration rate must be reduced to minimize the uneven loading of the cutters and the main bearing. Utilization also drops due to increased necessity of surveying and repositioning of the surveyor's laser reference. Backup systems often experience difficulties in negotiating curves, as well. Towed sleds tend to ride up the inside of the curve while rail-mounted backup units derail more often. The muck transfer and loading conveyors and the tunnel service lines must be adjusted continually to account for the positioning of each segment of the TBM support deck. These details all contribute to machine delays and subsequently to reduced utilization.

2.1.5 Crew Training and Motivation

Each TBM project undergoes a learning period during which system bugs are resolved and the crew develops a work rhythm. All TBM manufacturers provide experienced help for this startup phase in order to minimize delays, but machine utilization remains lower during this period than any other (barring catastrophe).

2.1.6 Access for Site Characterization

The high level of characterization required during excavation of the ESF openings could significantly reduce machine utilization. The amount of reduction will depend on the ease of access to the face and the area directly adjacent to and behind the machine, which in turn depends on the machine design and the tests to be conducted there.

2.2 The Mobile Miner

Performance was predicted for Mobile Miners excavating a 14 ft by 22 ft (4.3 m by 6.7 m) tunnel and a 16 ft by 30.5 ft (4.9 m by 9.3 m) tunnel. The former represents approximately the same cross-sectional area as that excavated by a 19 ft (5.8 m) diameter TBM. The latter provides the same area as a 25 ft (7.6m) diameter TBM. Table 4 presents the performance prediction results.

Table 4

Performance prediction of Mobile Miners in two opening shapes in the potential repository horizon (TSw2 unit)

PARAMETER	14 X 22 ft OPENING	16 X 30.5 ft OPENING
cutterhead diameter (ft)	14	16
width of cut (ft)	22	30.5
sweep radius (ft)	19	22.5
sweep angle (deg)	68.5	82
rotational speed (rpm)	14	11
cutters (total/center/gage)	15 /7 /8	15 /7 /8
cutterhead power (# motors @ hp)	2 @ 350	2 @ 450
max operating torque (ft-lbf)	262,000	429,700
penetration per sweep (in.)	0.33	0.36
sweep time (sec)	25.5	35
plunge time (sec)	3	3
penetration rate (ft/hr)	3.5	2.8
cutter life (hrs)	70	72
tunnel length per cutter (ft)	243	201
approx cutter cost ($/yd^3)	8.50	7.80

The Mobile Miner is not intended to compete with TBMs in advance rate or production rate. It is inherently incapable of TBM ratesby virtue of its mobility, which requires less mass and a lessrigid structure. Fewer cutters contact the rock than for a TBM in a similarly sized opening (e.g., in the smaller opening, three versus 34 cutters). Unlike the full-face TBM, the Mobile Miner attacks only a small portion of the tunnel face at any given time. However, the Mobile Miner is better able to bore openings with flat floors, to turn through small radii, and to tram about the excavation. It also allows ready access to the face for inspection, support installation, and dewatering.

As expected, the attainable penetrations with the Mobile Miner are much less than for either TBM configuration. The cuttercosts for the Mobile Miner are higher due to lower system rigidity and the cyclic contact of the cutters with the rock.

The utilization percentage and subsequent advance rates for the Mobile Miner depend on the same factors as those discussed in the previous section for TBMs, with some modifications. Again, a considerable degree of judgment and experience is required to estimate a realistic utilization percentage. Note that the utilizations are lower than for the TBMs, as follows from the discussions below. Table 5 summarizes the estimated utilizations and the advance rates for construction of both sizes of opening with a Mobile Miner. See Section 2.1 for a discussion of scenario number.

Table 5

Projected Advance Rates of Mobile Miners in Two Opening Sizes in the Potential Repository Horizon (TSw2). Each scenario illustrates a condition likely to be found in ESF construction. (See Figures 18 and 20 for graphical comparison to other machines.)

14 ft by 22 ft OPENING:

scenario number	slope %	curve radius (ft)	RQD %	penetration rate (ft/hr)	utiliz. %	advance rate (ft/day)
1	-1 to +3	none	50+	3.5	40	34
2	-1 to +3	none	25 to 50	3.5	30	25
3	-8.9	none	50+	3.5	35	29
4	-14 to -21	none	50+	3.5	30	25
5	-8.9 to -21	none	25 to 50	3.5	24	20
6	-1 to +3	100	50+	3.0	30	22
7	-8.9 to -21	100	50+	3.0	27	19

16 ft by 30.5 ft OPENING:

scenario number	slope %	curve radius (ft)	RQD %	penetration rate (ft/hr)	utiliz. %	advance rate (ft/day)
1	-1 to +3	none	50+	2.8	45	30
2	-1 to +3	none	25 to 50	2.8	35	24
3	-8.9	none	50+	2.8	40	27
4	-14 to -21	none	50+	2.8	37	25
5	-8.9 to -21	none	25 to 50	2.8	30	20
6	-1 to +3	100	50+	2.3	35	19
7	-8.9 to -21	100	50+	2.3	33	18

2.2.1 Slope and Haulage System

Similar to a TBM operation, the Mobile Miner is affected by slopes, based on general inconvenience, water drainage problems,and changed material haulage energy requirements.

The choice of haulage system was not as critical for the Mobile Miner as it was for the TBM simply because of the smaller amounts of rock produced. For example, at the estimated penetration rate of 3.5 ft/hr (1.1 m/hr), 72 tons (65 mt) of muck were produced from the smaller opening. This quantity could be removed easily with a conveyor system or with a large capacity (8 to 10 ton or 7 to 9 mt) rubber-tired loader.

2.2.2 Curves

Since one of the design features of the Mobile Miner is its ability to maneuver around relatively tight curves, 100 ft (30 m) radius curves should not affect performance. Machine utilization would be reduced somewhat by the detailed surveying necessary to maintain high accuracy in curve shape. Where very sharp turns must be cut (e.g., near-90°), the machine must be repositioned and must cut slowly for a time to establish the required face profile before resuming full-speed cutting.

2.2.3 Rock Quality

Because of the lower penetration rates, rock quality is not expected to have as strong effect on the performance of the Mobile Miner as it has on TBM performance. However, due to the overhung face profile, the Mobile Miner may not be suitable for rock with an RQD of less than 25%. Unlike a TBM, the Mobile Miner is designed for simultaneous excavation and roof support installation near the face.

2.3 <u>Roadheaders</u>

As noted previously, the welded tuffs of the potential repository horizon can be excavated with heavy duty roadheaders. It should be noted that excavating the TSw2 unit will require a machine at the edge of roadheader technology. In essence, a roadheader is technically able to excavate very hard rock, but fails economically because of excessive cutter wear resulting in high operational costs. Table 6 lists the specifications of the presently available machines of that type, and Table 7 shows the predicted performance of a typical 100 ton (91 mt) machine in the TSw2 thermomechanical unit. Table 6 was included to give examples of present roadheader technology. These machines have been used extensively in industry and have established a track record. They are very effective in complex openings.

As expected, the cutter costs for the roadheader were higher than for the TBMs or the Mobile Miner. This is because in hard, abrasive materials such as welded tuff, the drag-type cutter bits which roadheaders use suffer extensive wear and require frequent replacement. Despite the high bit costs, roadheaders still should be considered for various aspects of ESF construction because of their high mobility, versatility, and their ability to excavate openings of varied size and shape.

Utilization factors and, consequently, advance rates were not determined for the roadheader simulation. This was due to the fact that roadheaders have not been used in rock as hard as TSw2 often enough that an accurate estimate could be made.

Table 6

Specifications For Some Heavy-duty Roadheaders From Various Manufacturers

Manufacturer	Machine Model	Weight (tons)	Dimensions (ft)	Cutterhead Power (hp)	Pump Type	Hydraulic System Pressure (psi)	Arc Force (tons)	Lift Force (tons)
Anderson Strathclyde PLC 47 Broad Street Glasgow G40 2QW Scotland	RH-90	100	L = 35.0 H = 8.5 W = 11.4	std = 200 max = 400 1000 vac 60 Hz	300 hp drive	1950	21-27	17-25
Atlas Copco / Eichoff Hunscheidtstrasse 154 4630 Bochum 1 W. Germany	ET 400	123	L = 56.5 H = 7.7 W = 12.0	std = 400 max = 670 1000 vac 60 Hz	130 hp drive	3150		
Dosco Overseas Eng. Ollerton Road Tuxford Nr Newark Notts NG22 0PQ England	MK-III	93	L = 40.0 H = 9.6 W = 13.0	std = 230 max = 400 1000 vac 60 Hz	180 hp drive	2000	15.6	10.8 (lower = 15.5)
Eimco International Earlsway, Team Valley Gateshead, NE11 0SB England	Bert 1100	123		std = 200 1000 vac 60 Hz				
Paurat GmbH P.O. Box 02 12 20 D-4223 Voerde W. Germany	E 242	134	L = 54.3 H = 12.8 W = 13.3	std = 200 max = 400 1000 vac 60 Hz	120 hp drive	3500	13.3	13.3 (lower = 13.3)
Voest Alpine GmbH P.O. Box 1 Zeltweg A-8740 Austria	AM100-300C	97	L = 40.5 H = 6.0 W = 10.2	std = 400 1000 vac 60 Hz	270 hp drive	3000-3500	13.3	13.3 (lower = 13.3)
Westfalia Lunen D-4670 Lunen W. Germany	WAV 178/300	82	L = 51.3 H = 10.0 W = 13.8	std = 400 1000 vac 60 Hz	120 hp drive			

Table 6

Specifications For Some Heavy-duty Roadheaders From Various Manufacturers (continued)

Manufacturer	Type	Number of Bits	Cutter Head Lacing	Cutter Head Diameter (inches)	Speed (rpm)	Bit Tip Speed (ft/min)
Anderson Strathclyde PLC 47 Broad Street Glasgow G40 2QW Scotland	axial	48	3 start	39	21 30	245 350
Atlas Copco / Eichoff Hunscheidtstrasse 154 4630 Bochum 1 W. Germany	transverse axial	128 56	3 start 1 start	31 36		
Dosco Overseas Eng. Ollerton Road Tuxford Nr Newark Notts NG22 0PQ England	axial	56	3 start	36	32 60	301 565
Eimco International Earlsway, Team Valley Gateshead, NE11 0SB England						
Paurat GmbH P.O. Box 02 12 20 D-4223 Voerde W. Germany	axial	56	1 start	48	20.4 41.2	251 505
Voest Alpine GmbH P.O. Box 1 Zeltweg A-8740 Austria	transverse	78	3 start	35	86.9	785
Westfalia Lunen D-4670 Lunen W. Germany	transverse	154	4 start	33.5	90	690

Table 6

Specifications For Some Heavy-duty Roadheaders From Various Manufacturers (concluded)

Manufacturer	Dimensions (ft)	Tracks Type	Ground Pres (psi)	Speed (ft/min)	Cutting Height (ft)	Cutting Width (ft)	Sumping Force (tons)
Anderson Strathclyde PLC 47 Broad Street Glasgow G40 2QW Scotland		Caterpillar	21.5	6.5	max = 16.4 min = 9.8	max = 19.7 min = 13.0	60
Atlas Copco / Eichoff Hunscheidtstrasse 154 4630 Bochum 1 W. Germany			29	13.7	max = 20.4 min = 9.8	max = 27.3 min = 13.0	74
Dosco Overseas Eng. Ollerton Road Tuxford Nr Newark Notts NG22 0PQ England	L = 15.7 W = 2.0	D-8 Caterpillar 3-bar grouser	20	0-21	max = 20.3 min = 11.5	max = 23.5 min = 14.7	61
Eimco International Earlsway, Team Valley Gateshead, NE11 0SB England			14.2				
Paurat GmbH P.O. Box 02 12 20 D-4223 Voerde W. Germany		D-8 Caterpillar	25	0-60	max = 24.8 min = 14.0	max = 29.3 min = 14.7	34
Voest Alpine GmbH P.O. Box 1 Zeltweg A-8740 Austria		VA piano	25	10-27	max = 17.6 min = 7.8	max = 23.8 min = 14.7	64
Westfalia Lunen D-4670 Lunen W. Germany	W = 2.5	unitrac or D-8 type	22	59 (both types)	max = 25.2 min = 16.5	max = 30.0 min = 14.7	

Table 7

Performance prediction of a heavy-duty roadheader in the potential repository horizon (TSw2 unit)

HEAVY-DUTY ROADHEADER:

cutterhead diameter	40 in.
rotational speed	25 rpm
cutters	Sandvik 84HCT (drag type)
cutter penetration angle	56°
cutter spacing	2.0 in.
cutter speed	250 ft/min
max cutter load	30,000 lbf
cutterhead power	400 hp
penetration rate	2.6 ft/hr
approx cutter costs	12.50 $/yd^3

2.4 Blind Shaft Borers

In all but the hardest rocks, the performance of a BSB is governed by the support system rather than by the geology and the rock conditions. This is due to the limited haulage capacity of the hoisting skips and the requirement that the shaft lining be placed closely behind the machine for safety. The effectiveness of the muck pickup at the face also is a concern since the broken rock must be moved against gravity. These factors combined emphasize that a BSB is limited by the backup rather than its excavation ability.

The expected performances of both a high-speed BSB and a low-speed BSB were calculated, as shown in Table 8. The penetration rate for both machines was fixed at 6.0 ft/hr (1.8m/hr) to account for the limitations imposed by hoisting and lining considerations. This formed the basis for the remainder of the calculations.

Cutter costs were lower for the low-speed simulation, since the cutters were loaded to near capacity and penetrated deeper during each revolution of the cutterhead. This meant a smaller distance traveled per cutter for each foot of shaft excavated, and thus, lower cutter wear on the same basis. Despite these advantages of low speed operation, however, the high speed option may be preferred for the following reasons:

1. If harder rock were encountered, increasing the rotational speed would be the only means available to fully utilize the installed cutterhead power.

Table 8

Performance Prediction of Two Blind Shaft Borers (BSB) Speeds in the Potential Repository Horizon (TSw2 unit)

PARAMETER	BLIND SHAFT BORER: HIGH SPEED	LOW SPEED
cutterhead diameter (ft)	18	18
rotational speed (rpm)	8.2	6.15
cutters (# @ diameter (in.))	35 @ 17	35 @ 17
max cutter load (lbf)	50,000	50,000
cutterhead power (# motors @ hp)	3 @ 375	3 @ 375
max operating torque (ft-lbf)	720,500	960,700
operating thrust (lbf)	1,750,000	1,750,000
penetration / revolution (in.)	0.15	0.20
penetration rate (ft/hr)	6	6
cutter life (hrs)	80	106
shaft length per cutter (ft)	479	636
approx cutter cost ($/yd^3)	8.07	6.08

2. Regardless of the muck pickup method used, higher cutterhead speeds clean the face more effectively.

The estimated utilization factor for the BSB was about 30%, taking into account the hoisting and lining requirements. Thus a daily advance rate of 43 ft (13 m) appeared feasible. This assumed that two 20 ft (6.1 m) high rings of concrete lining could be poured per day to keep pace with the machine advance.

2.5 Vertical Wheel Shaft Boring Machines

As previously described, the SBM excavates rock with a vertical wheel dressed with standard TBM disk cutters, attacking and breaking the rock in much the same way as the Mobile Miner does. As with the BSB, the SBM forms the centerpiece of an integrated shaft construction system that includes muck hoisting, shaft lining, and dewatering. Table 9 lists machine specifications and performance results.

Since the vertical wheel SBM is a new design concept, no field data exists with which to estimate its expected utilization factors and advance rates. Field data from other types of shaft borers indicate that SBM utilization likely would be in the range of 30%. The advance of this machine also would be limited mainly by the support activities: the predicted daily advance was approximately 30 ft (9.1 m), allowing two concrete lining pours of 15 ft (4.6 m) each.

Table 9

Performance Prediction of a Vertical Wheel Shaft Boring Machine (SBM) in the Potential Repository Horizon (TSw2 unit)

VERTICAL WHEEL SHAFT BORING MACHINE:	
cutterwheel diameter	18 ft
rotational speed	9 rpm
traverse speed	0.95 rpm (around shaft)
cutters	16 @ 17 in. diameter
cutter spacing	4.0 in. (at perimeter)
max cutter load	50,000 lbf
cutterhead power	2 motors @ 400 hp
max operating torque	396.8×10^3 ft-lbf
operating thrust	348×10^3 lbf
penetration per traverse	0.89 in.
penetration rate	4.2 ft/hr
cutter life	26 hrs
shaft length per cutter	109 ft
approx cutter costs	5.25 $\$/yd^3$

2.6 Raise Drills

As mentioned previously, constructing a shaft by raise boring is a two step process. First, a pilot hole is drilled in the desired location, then a reamer enlarges the hole to its final diameter. For a 18 ft (4.9 m) diameter shaft, the drill pipe would be 11.25 or 12.875 in. (29 or 33 cm) in diameter with a 12.25 or 13.75 in. (31 or 35 cm) diameter pilot bit, respectively.

The most powerful raise drills available today can achieve a penetration rate as high as 40 ft/hr (12 m/hr). However, in general, pilot bit penetration is limited to about 3 to 6 ft/hr (0.9 to 1.8 m/hr) to minimize hole deviation.

For this study, a Robbins model 103 RM-DC raise drill was assumed, with specifications as listed in Table 10. An 18 ft (4.9 m) diameter reamer head would be a custom design. The head was assumed to be fitted with 26 disk cutters of the four-row, tungsten-carbide insert type. The cutters would be spaced 2.0 in. (5.1 cm) apart.

The 6 ft (1.8 m) diameter reamer head is a standard size, available off the shelf. A Robbins model RR6E was chosen for this part of the analysis. The reamer mounts 10 cutters, each containing four 15.5 in. (39 cm) diameter disk cutters set with tungsten-carbide inserts. It was analyzed not for comparison with the larger raise drill, but as a means of creating the pilot hole for the V-Mole (next section).

Table 10

Performance Prediction of Two Sizes of Raise Drills in the Potential Repository Horizon (TSw2 unit). Note that the small raise drill was intended for use in conjunction with the V-Mole (Table 11). See Figure 21.

PARAMETER	RAISE DRILL DIAMETER: 18 ft	6 ft
pilot string diameter (in.)	12.875	10
pilot bit diameter (in.)	13.75	11
reaming head diameter (ft)	18	6
rotational speed (rpm)	6	10
cutters with tungsten-carbide inserts		
(# cutters @ # disks/cutter)	26 @ 4	10 @ 4
cutter spacing (in.)	2.0	2.0
max cutter load (lbf)	50,000	65,800
cutterhead power (hp)	400	300
max operating torque (ft-lbf)	258,500	44,100
operating thrust (lbf)	1,307,000	492,300
penetration / revolution (in.)	0.08	0.09
penetration rate (ft/hr)	2.28	8.1
cutter life (hrs)	560	480
shaft length per cutter (ft)	1280	3900
approx cutter costs ($/yd^3)	18.50	17.40

The utilization factors and advance rates of the raise drills were influenced by all the factors discussed with the TBMs, except haulage. The shaft was vertical, with no curves, and no substantial quantities of water were anticipated; these factors had negligible impact on the utilization percentage.

Rock quality could have a significant impact on the feasibility of raise drill application. Raise drills can operate in a wide variety of ground conditions unless the rock is highly fractured or blocky to the extent that the shaft caves and collapses around the reamer. In a vertical shaft, this would mean virtually running ground (very low cohesion) which is not expected to be encountered at Yucca Mountain.

Two additional issues, however, were important for estimating utilization. The first was the speed with which the drill pipe sections could be removed during reaming. The faster the sections can be taken off the string, the higher the utilization. The second issue was whether the cutters would survive for the length of the shaft without forcing the reamer to be withdrawn to replace them (called a bit trip). This issue was particularly critical since, depending on the shaft length and the ground conditions, a bit trip could result in significant equipment downtime. The reamer also might stick when pulled back up the hole to restart, since the new bits would be slightly larger than the old, worn ones were. Ideally, the entire shaft would be completed before the cutters would require changing. This was the situation assumed in the potential repository horizon, in which the projected minimum wearout distance for the carbide cutters was judged at approximately 1300 ft (400 m). The shaft was designed to be 1185 ft (360 m) deep.

Personnel access to the face for characterization and testing of the rock mass would require a bit trip each time, significantly reducing utilization.

Well-run raise drills often have utilization percentages of about 70%. Here, a conservative estimate of 60% was used for the larger machine, and 55% for the smaller one. The latter estimate was lower due to the faster penetration rate and the relatively longer time needed to change drill pipes.

The much higher penetration rate given by the small raise drill still overwhelms the lower utilization percentage to give an average daily advance of 107 ft (33 m). This is in contrast to 33 ft/day (10 m/day) for the large raise drill. Recall, however, that the two sizes are not intended to compete directly. The time needed to go the full distance with the small raise drill must be added to the shaft completion time using the V-Mole before comparison with the project duration of the large raise drill. This is discussed in Section 4.

2.7 The V-Mole

The V-Mole is similar in principle to the BSB except that it uses a predrilled pilot hole for muck disposal, thus requiring previously developed underground access. An 18 ft (4.9 m) diameter V-Mole needs a 6 ft (1.8 m) diameter pilot hole for effective muck removal. The machine has a V profile cutterhead so that gravity forces the cuttings into the pilot hole and down to the haulage level. The pilot hole also can be used for machine guidance during the reaming operation to achieve the shaft straightness needed for hoist operation later.

Performance in the potential repository horizon was predicted for a standard V-Mole and for an upgraded version. The results are listed in Table 11 along with the machine specifications. The upgraded unit used a higher speed cutterhead, larger cutters, more power, electric rather than hydraulic drives, and a dome-shaped cutterhead. The domed cutterhead applies load in a more effective direction and needs fewer cutters. It also is less susceptible to unwanted direction changes due to deviation of the pilot hole.

Utilization factors and advance rate of the V-Mole are governed by the speed with which support tasks can be accomplished. Including lining capabilities, a daily advance of 40 ft (12.2 m) was achieved, assuming the previous existence of a 6 ft (1.8 m) diameter pilot hole. Project scheduling would have to take into account the time needed to drill the pilot hole, as discussed in the previous section.

Table 11

Performance Prediction of Two V-Mole Configurations in the Potential Repository Horizon (TSw2 unit)

PARAMETER	V-MOLE: STANDARD	UPGRADED
cutterhead diameter (ft)	18	18
rotational speed (rpm)	6	8
cutters (# @ diameter (in.))	34 @ 14	23 @ 17
max cutter load (lbf)	35,000	50,000
cutterhead power (hp)	900	1200
max operating torque (ft-lbf)	551,500	669,600
operating thrust (lbf)	1,190,000	1,150,000
penetration / revolution (in.)	0.16	0.20
penetration rate (ft/hr)	4.8	8.0
cutter life (hrs)	75	63
tunnel length per cutter (ft)	360	504
approx cutter costs ($/yd^3)	13.80	5.55

3.0 PERFORMANCE RESULTS IN OTHER TUFF UNITS

Performance predictions for the two TBM designs also were made for the remaining thermomechanical units of the Topopah Spring and the Calico Hills Members of the Paintbrush Tuff (see Table 1 and Figure 1 for their respective physical properties). The discussion of utilization factors given in Section 2.1 applies to this analysis as well. Only the strength of the rock being excavated was changed from the analyses discussed in the previous chapter. Table 12 lists the results (see Table 2 for machine configurations); note that the advance rates were determined for the excavation of a level 25 ft (7.6 m) diameter drift with no curves. From Table 3, this size and type of TBM excavation was assumed to have a utilization factor of 55%. Advance rates for other scenarios of the preliminary excavation design can be determined by applying the appropriate utilization percentages from Table 3 (and expressing the results for a 24 hour day) to the penetration rates listed below. Figures 16 and 17 visually compare the advance rates and the cutter costs for the different thermomechanical units. Note the striking effect of the lithophysae density on machine performance. Without the increase in porosity provided by the lithophysae, cutters wear quickly in the TSw1 unit.

Table 12

Performance Prediction of Two TBM Configurations in All Tuff Units, Excavating a Level 25 ft (7.6 m) Diameter Drift With No Curves (utilization 55%). See Table 1 for rock unit codes.

STANDARD TBM:

Unit	instant. penetr. (in/rev)	penetr. rate (ft/hr)	advance rate (ft/day)	cutter life (hrs)	cutter life (ft of tunnel)	cutter costs ($/yd³)
TSw1 (LR)	0.70	22.3	294	202	4,506	0.73
TSw1 (G-2)	0.18	5.6	74	62	344	5.91
TSw1 (GU-3)	0.44	14.0	185	98	1,369	1.67
TSw2	0.18	5.7	75	66	376	5.41
TSw3 (G-2)	0.62	19.7	260	113	2,226	1.10
TSw3 (G-4)	0.40	12.7	168	94	1,195	1.87
CHn1v	0.31	9.7	128	86	836	2.56
Chn1z	0.70	22.3	294	160	3,565	0.82

HIGH POWER TBM:

Unit	instant. penetr. (in/rev)	penetr. rate (ft/hr)	advance rate (ft/day)	cutter life (hrs)	cutter life (ft of tunnel)	cutter costs ($/yd³)
TSw1 (LR)	0.75	26.2	346	224	5,889	0.96
TSw1 (G-2)	0.22	7.7	102	68	525	6.24
TSw1 (GU-3)	0.55	19.2	253	109	2,091	1.78
TSw2	0.25	8.8	116	73	637	5.15
TSw3 (G-2)	0.75	26.2	346	125	3,289	1.22
TSw3 (G-4)	0.50	17.5	231	104	1,821	2.01
CHn1v	0.37	12.9	170	95	1,230	2.79
Chn1z	0.75	26.2	346	177	4,642	1.05

4.0 DISCUSSION OF THE RESULTS

As expected, the different mechanical excavator designs respond quite differently to the known physical properties of the welded tuff units.

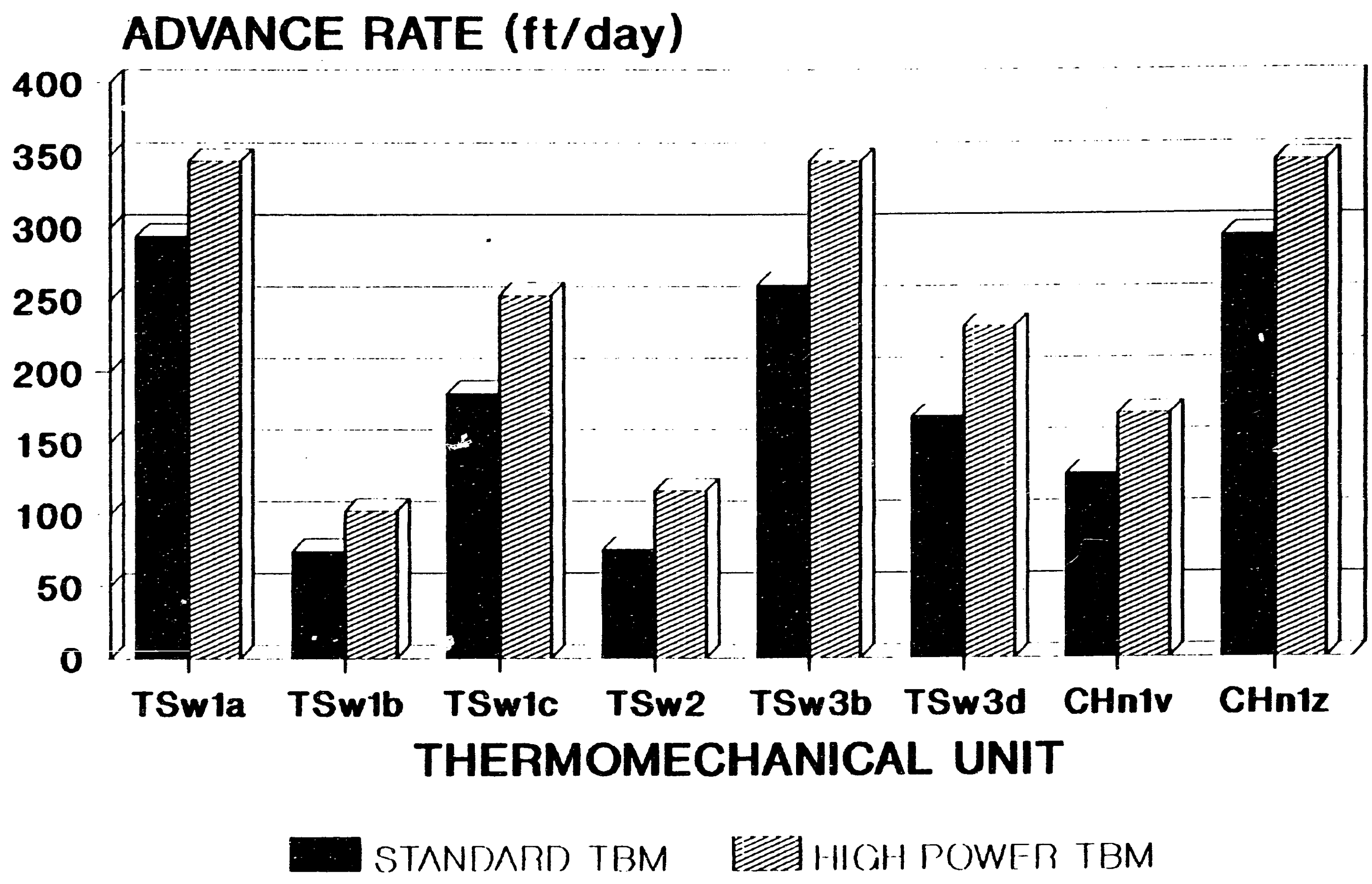


Figure 16. TBM Advance Rates For All Yucca Mountain Tuff Units Considered

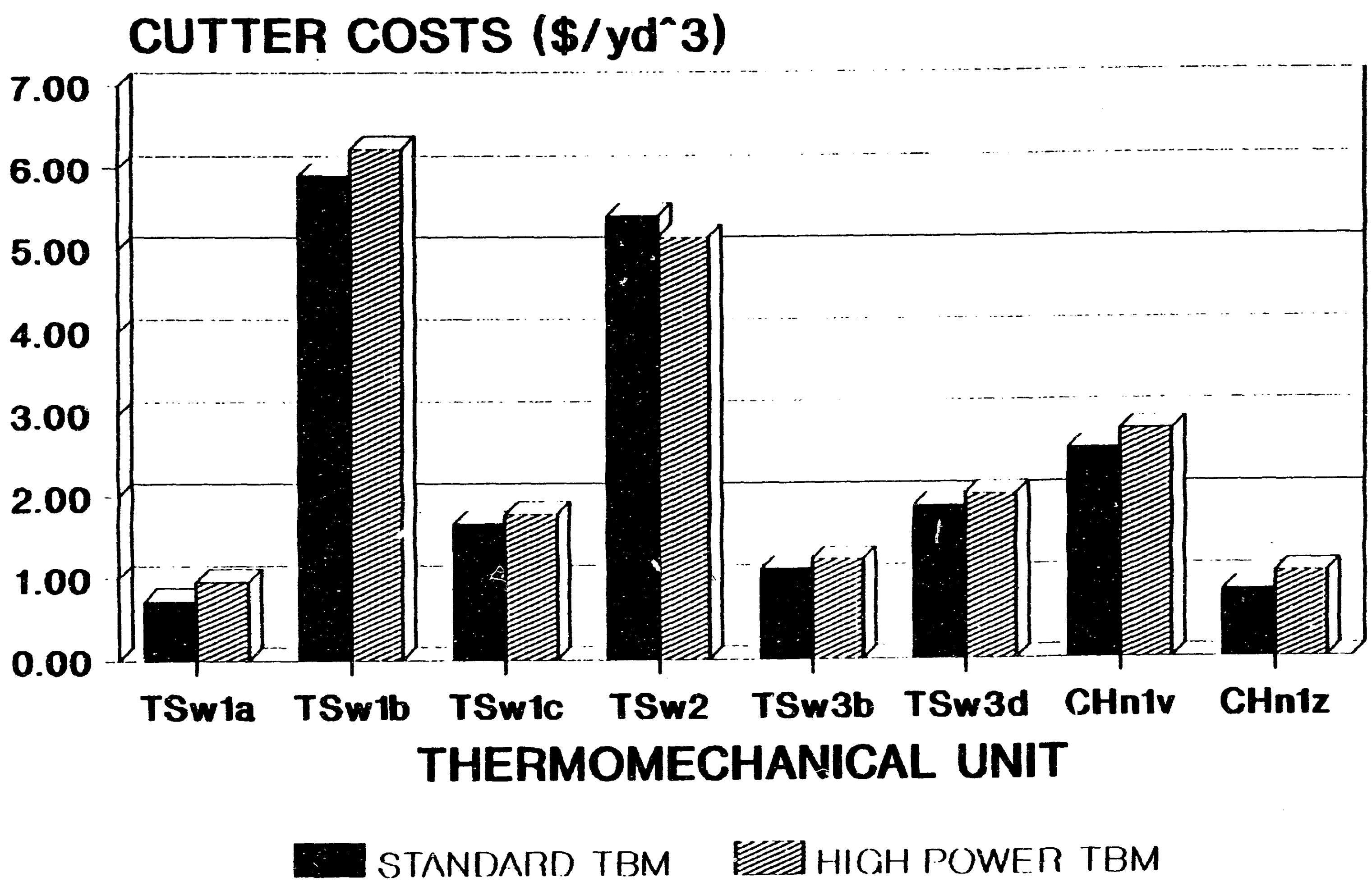


Figure 17. TBM Cutter Costs For All Yucca Mountain Tuff Units Considered

The full-face machines (the TBMs and the BSB) easily outpaced the partial-face machines, particularly the roadheaders, in all of the rock types (Figure 18). However, daily advance is not the whole story.

The economics of the design choices are as important as advance rate, if not more so; economics are represented here by the cutter costs, as per standard industry practice (Figure 19). The costs of maintaining the cutters reflect the efficiency and appropriateness of the machine design for the rock conditions. In the ideal case, the fastest machine would have the lowest cutter costs, but mechanical excavator design remains more empirical than theoretical. Such a level of precision has not been reached in either machine design or rock mass characterization. Both would be necessary for a perfect match of machine to rock in any given case.

Comparison of Figure 18 with Figure 19 reveals the differences between advance rate and cutter costs as decision variables for choosing excavators. A final decision must achieve a balance between the two, while accommodating the factors which affect machine utilization.

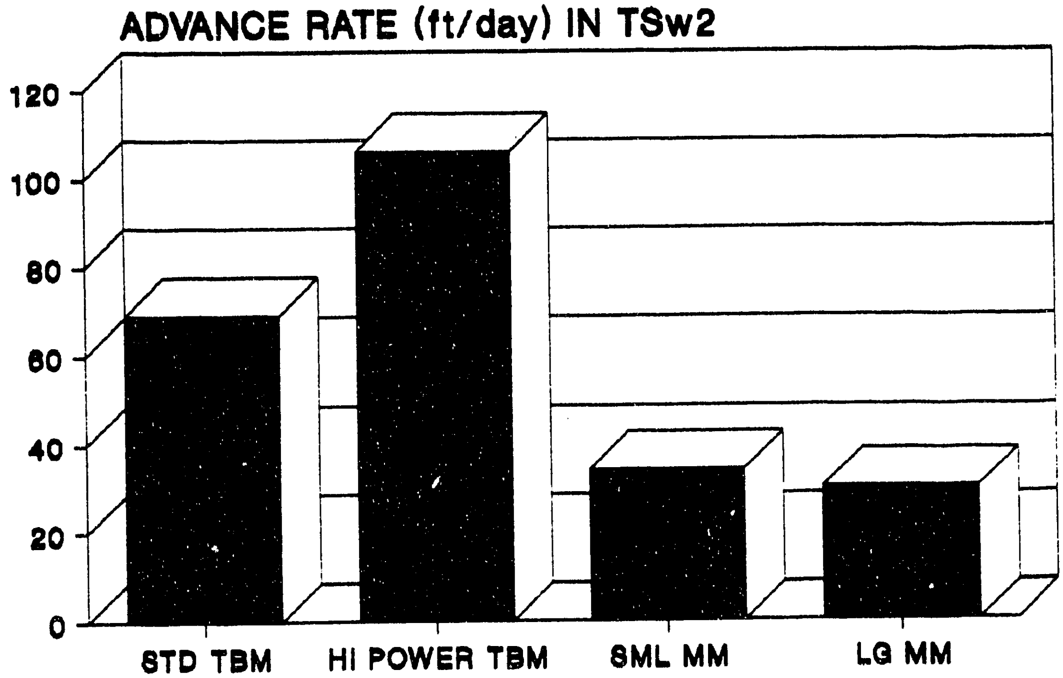
Figure 20 shows how the varying tunneling conditions within the preliminary ESF design can affect the advance rate through their effects on utilization percentage (scenario descriptions are found in Tables 3 and 5).

Differences between mechanical excavation of tunnels (horizontal openings) and shafts also must be borne in mind. The capacity of muck-handling systems imposes a rather severe limit (in this case, approximately 40 ft/day or 12 m/day) on the achievable production rate of the faster shaft borers. In situations where underground access already has been established, this can be resolved by boring upwards instead of downwards, as for example using a raise drill rather than a BSB. Figure 21 compares in graphical form the estimated time to completion of a 18 ft (4.9m) diameter, 1185 ft (360 m) deep shaft using the various shaft borers studied. The figure does not take into account the time necessary to establish underground access as required for some of the techniques, but it does include the time needed to drill the pilot raise for the raise drill and V-Mole.

For both tunnels and shafts the characterization requirements of the ESF will alter the effect of some of the factors that are important in present-day civil and mining excavation. The need to monitor the rock mass in detail throughout the excavation process urges has been used as an argument for partial-face machines. Backing up a full-face excavator whenever face examination is needed would prolong the schedule significantly. Partial-face machines also might allow detection of perched water zones earlier. This assumes that dust does not obscure the face too much; perched water detection may be accomplished more readily by means of humidity sensors on ventilation return lines.

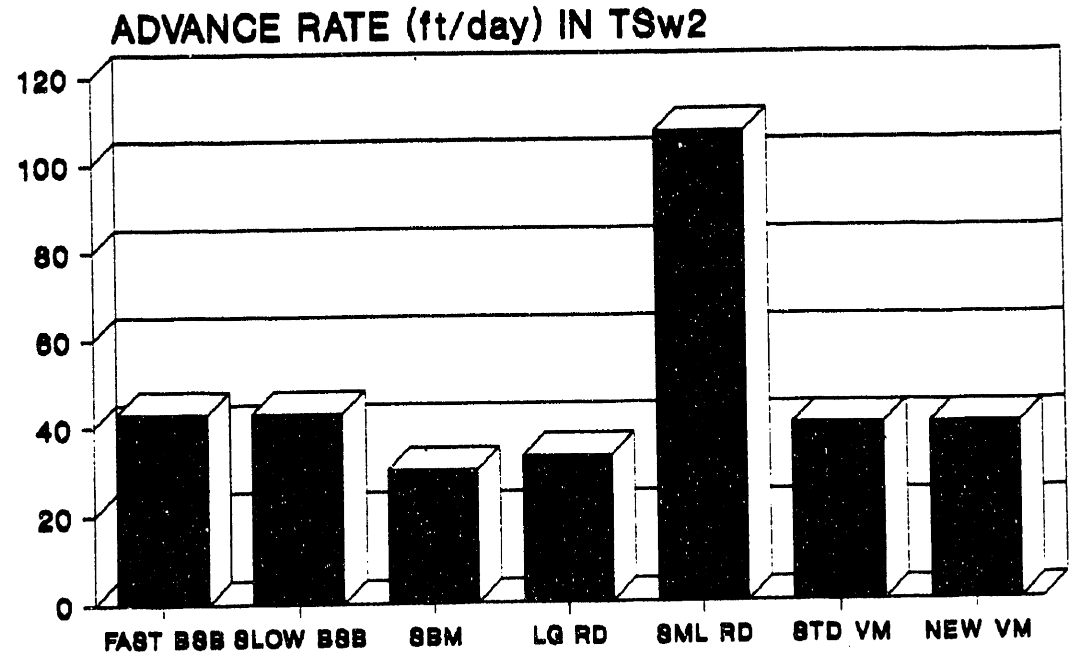
All the machine designs discussed in this report can perform without water sprays, as requested by the preliminary excavation plans, but consequently all will produce large amounts of dust. Ventilation will be a prime concern. Clouds of dust will obscure the face and thereby negate much of the flexibility that is available with the partial-face excavators. Vacuum

A



TBM = tunnel boring machine
MM = Mobile Miner

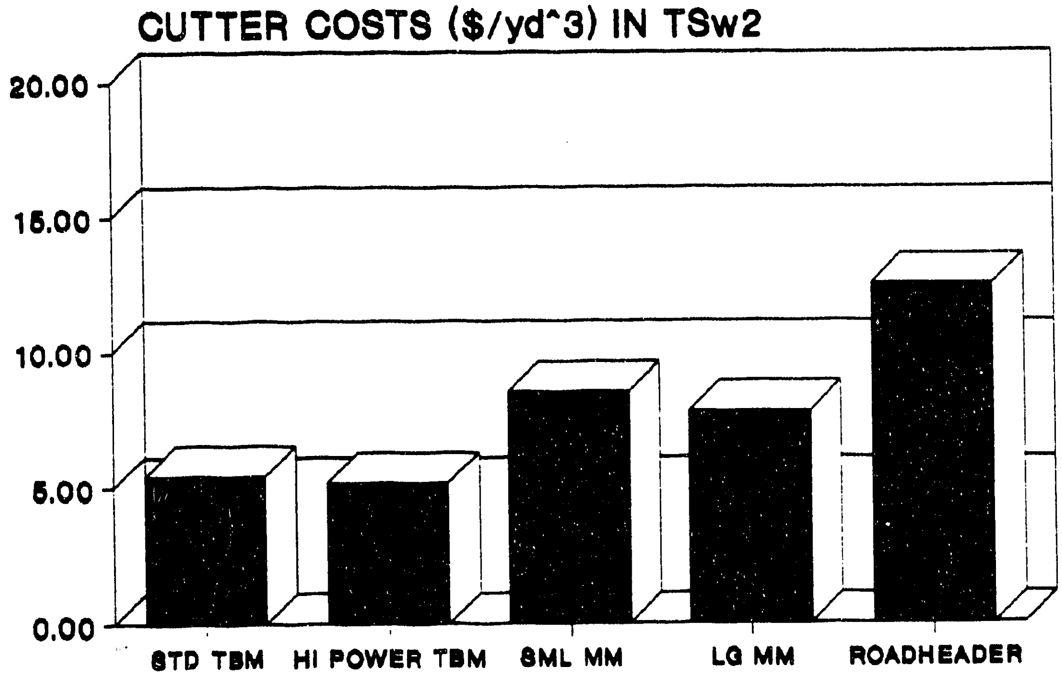
B



BSB = blind shaft borer
SBM = shaft boring machine
RD = raise drill, VM = V-Mole

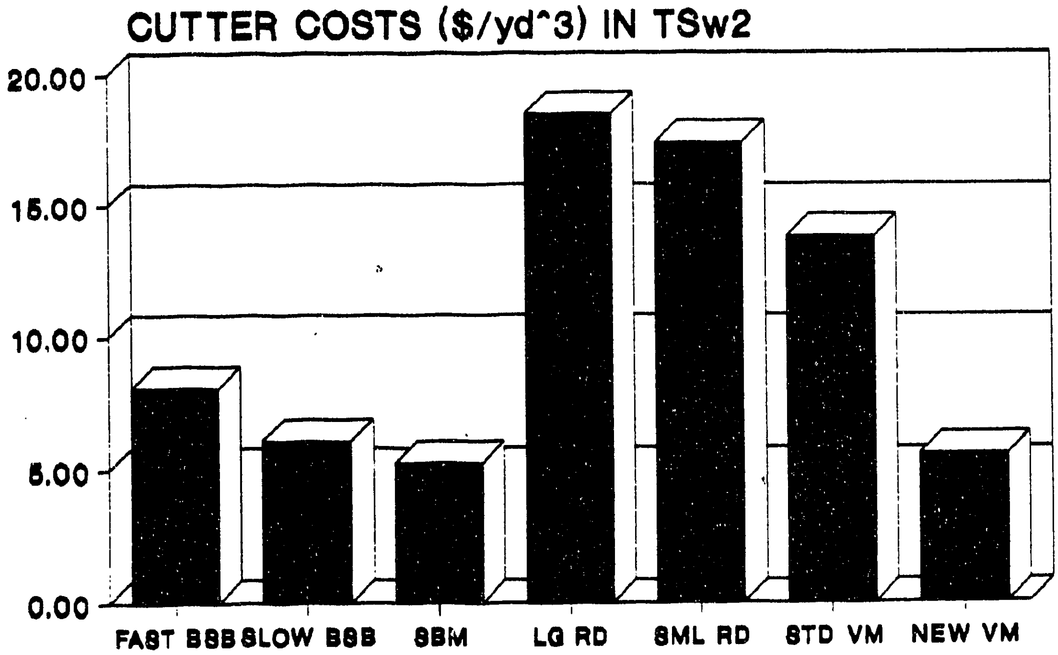
Figure 18. Advance Rates For Horizontal Excavators (A) and Shaft Borers (B) in the Potential Repository Horizon (TSw2)

A



TBM = tunnel boring machine
MM = Mobile Miner

B



BSB = blind shaft borer
SBM = shaft boring machine
RD = raise drill, VM = V-Mole

Figure 19. Cutter Costs For Horizontal Excavators (A) and Shaft Borers (B) in the Potential Repository Horizon (TSw2)

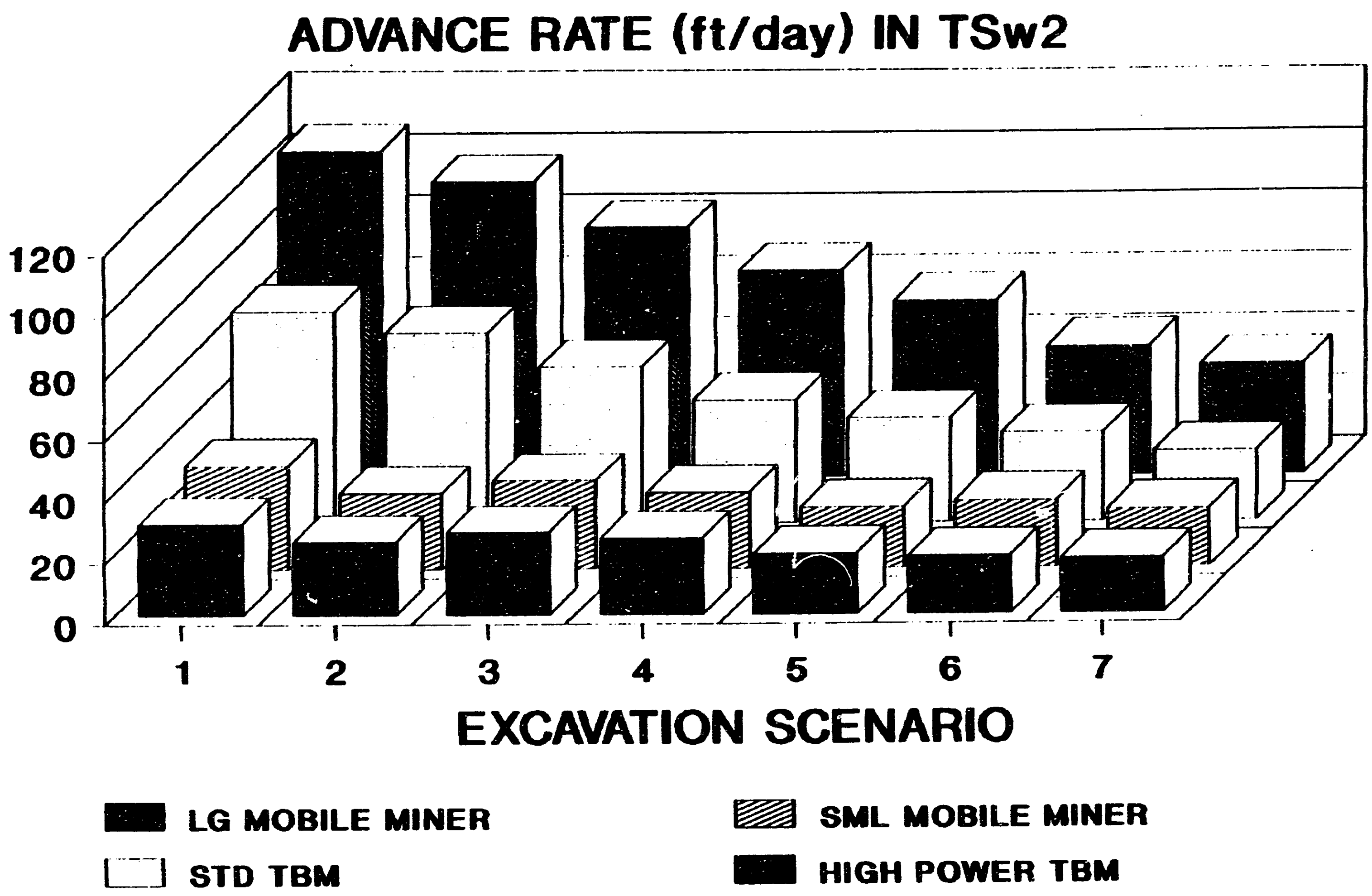


Figure 20. Effect of Excavation Scenario (See Tables 3 and 5) on TBM and Mobile Miner Advance Rates in the Potential Repository Horizon (TSw2)

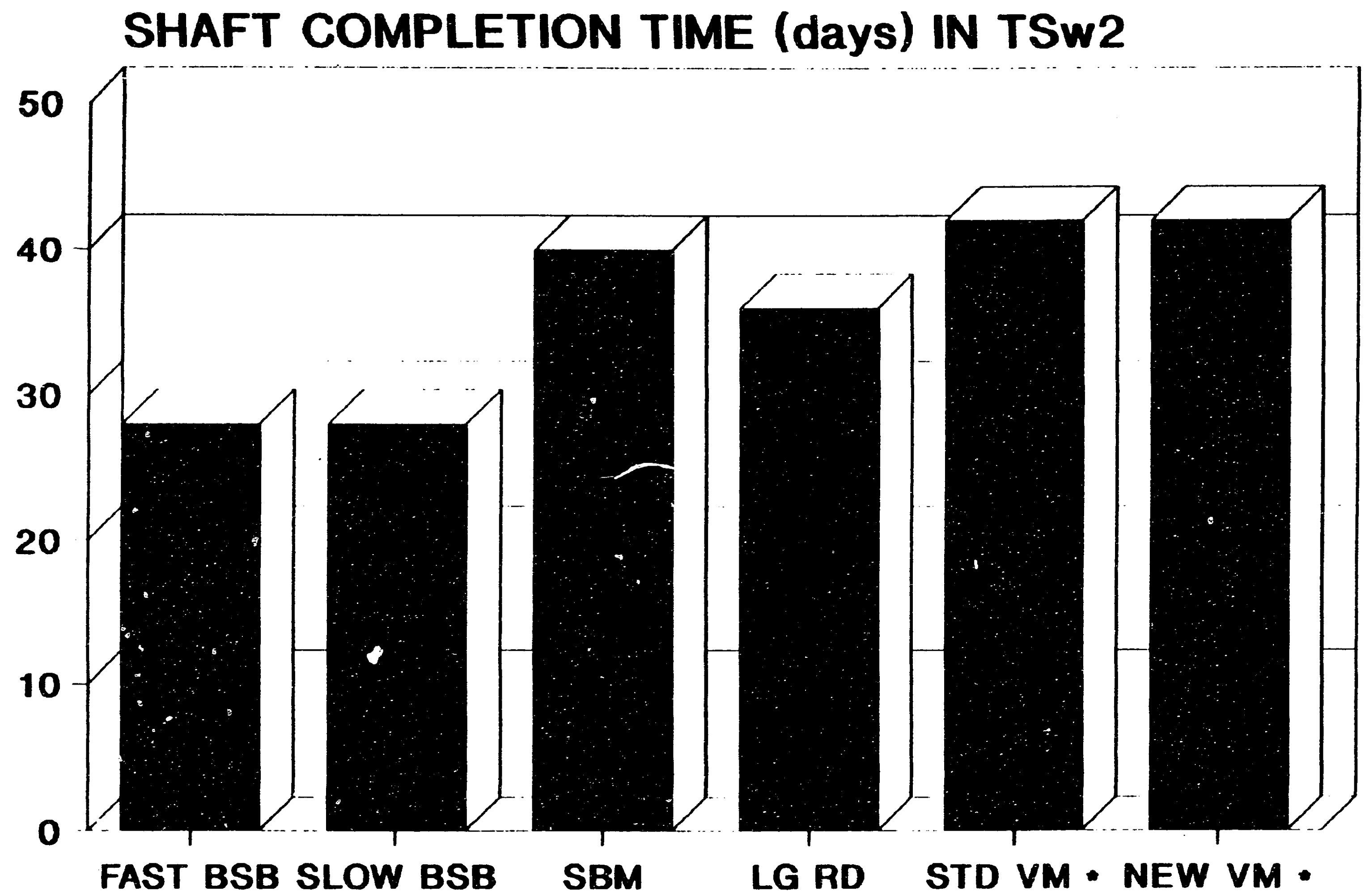


Figure 21. Estimated Time to Completion of Shaft Borers in the Potential Repository Horizon (TSw2)

removal of dust (and muck, in shaft drilling) is easier with full-face machines, although workable with any machine design.

5.0 CONCLUSIONS

The performance analyses presented and discussed in this report, although using incomplete information, indicate that mechanical excavation systems can economically and efficiently construct the openings required for the ESF. The machines examined here cover a broad range of designs and excavation principles, and therefore, capabilities. Innovations and site-specific modifications are being made continually by manufacturers worldwide. The special needs of ESF excavation can be met with few special modifications beyond those needed for cost-effective operation in welded tuff.

As discussed in more detail below, additional information about the behavior of the welded tuffs to be encountered at the ESF site would refine the performance predictions presented here. This would narrow the field of promising mechanical excavation systems. Physical property parameters of particular use to excavation machine design can be obtained with little trouble in any well equipped rock mechanics laboratory. These data will be acquired in Task 1.2 of this effort and will be used to refine the above predictions of machine performance in Task 1.3. A SAND report will be prepared discussing the complete results of Task 1 in detail.

6.0 RECOMMENDATIONS

The prediction of mechanical excavator performance would be greatly enhanced by additional data on the properties of the candidate tuff layers. Experience has shown that the toughness and abrasivity of the rock to be excavated cannot be adequately characterized by only density and compressive strength. In addition to these parameters, the following tests are required for realistic predictions of mechanical excavator performance:

1. Force-penetration tests - The force-penetration behavior of rock samples indicates directly the forces required to penetrate and fail the rock.

2. Tensile strength tests - The tensile strength and the ratio of tensile to compressive strengths are measures of the toughness of the rock fabric.

3. Acoustic measurements - Acoustic velocities of the rock provide indications of its competency and brittleness. This applies also to the dynamically determined elastic constants (Young's modulus and Poisson's ratio).

4. Cerchar abrasivity index - This direct abrasion test gives a strong indication of the cutter wear to be expected.

5. **Thin-section petrologic analysis - The percentage of quartz and other abrasive minerals, the angularity of their grains, and the microstructure (pores, microfractures) of the rock are best determined through thin-section petrologic analysis. Knowledge of mineralogic and microstructural characteristics allows good prediction of the wear to be expected on cutters.**

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APPENDIX I

Information from the Reference Information Base Used in this Report

This report contains the following information from the Reference Information Base (USDOE, 1989).

Table I-1

Uniaxial Compressive Strengths Used For Performance Evaluation, From RIB Version 4 (USDOE, 1989) (TS = Topopah Spring, CH = Calico Hills, w = welded, n = nonwelded, v = vitric, z = zeolitized)

THERMOMECHANCIAL UNIT	COMPRESSIVE STRENGTH (psi / MPa)
TSw1 (LR = lithophysae rich)	2,350 / 16
TSw1 (GU-3 = litho. poor, well USW GU-3)	10,000 / 175
TSw1 (G-2 = litho. poor, well USW G-2)	25,380 / 69
TSw2	22,480 +- 8,500 / 155 +- 59
TSw3 (USW G-2 = well USW G-2)	7,540 / 52
TSw3 (USW G-4 = well USW G-4)	10,880 / 75
CHnlv	13,050 / 90
Chnlz	3,770 / 26

These values were obtained directly from RIB Version 4 (USDOE, 1989), which was the current version at the time this SLTR was submitted.

Candidate Information
for the
Reference Information Base

This report contains no candidate information for the Reference Information Base.

Candidate Information
for the
Site & Engineering Properties Data Base]

This report contains no candidate information for the Site and Engineering Properties Data Base.

APPENDIX II

The following S.I./English conversion factors apply to the parameters used throughout this report:

1 meter (m)	=	3.28 ft or 39.4 in.
1 cubic meter m^3	=	1.307 yd^3
1 megapascal (MPa)	=	145.03 psi
1 metric ton (mt)	=	2.2 x 10^3 lbm or 1.1 tons
1 meganewton (MN)	=	225 x 10^3 lbf
1 kilowatt (kW)	=	1.34 hp
1 newton-meter (N-m)	=	0.737 ft-lbf
1 kilonewton (kN)	=	225 lbf

APPENDIX B

PHYSICAL PROPERTIES OF SOME WELDED TUFFS FOR PERFORMANCE PREDICTION OF MECHANICAL EXCAVATORS

by

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(Formerly SLTR90-7004)

Submitted 31 January 1991

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PHYSICAL PROPERTIES OF SOME WELDED TUFFS FOR PERFORMANCE PREDICTION OF MECHANICAL EXCAVATORS

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1.0 INTRODUCTION

The work described here was performed for Sandia National Laboratories (SNL) as part of the Yucca Mountain Site Characterization Project (YMP). SNL is one of the principal organizations participating in the project, which is managed by the U.S. Department of Energy's (DOE) Nevada Operations Office. The project is part of the DOE's Terminal Storage program to safely dispose of the radioactive waste from nuclear power plants.

The DOE has determined that the safest and most feasible method currently known to dispose of such wastes is to place them in mined geologic repositories. Various means of excavating the repositories are being examined, including mechanical excavators. The YMP is conducting detailed studies of an area on and near the Nevada Test Site (NTS) to determine the feasibility of developing a potential repository at depth in the welded tuffs at Yucca Mountain.

The data presented in this SLTR are intended to support performance prediction studies of mechanical excavators for the creation of a mined geologic repository at NTS. The data were gathered by the Earth Mechanics Institute (EMI) of Colorado School of Mines for Task 1.2 of Contract #35-0039 with SNL. The purpose of this Task was to supply additional physical property values needed for excavator performance prediction in welded tuff, as specified in the report for Task 1.1 (SLTR90-7003). Several of the physical property tests performed for this Task repeat work that has been reported previously (USDOE, 1990; Price et al., 1985; Price et al., 1987; and others). This was done to assure continuity and repeatability and to resolve property variation among different reports (see SLTR90-7003 for a complete bibliography of the references reviewed). The remainder of the tests, however, obtained physical properties not previously determined for welded tuffs at the Yucca Mountain site, yet which are commonly used in the design and production estimation of mechanical excavation systems.

The work discussed in this SLTR was conducted under the aegis of Work Breakdown Structure (WBS) element 1.2.4.2.1.3, titled "Rock Mechanics Field Testing". All efforts within this WBS element are scoping and developmental in nature, and are therefore considered nonquality affecting activities. Several quality assurance implementing procedures were utilized in the conduct of this work to be consistent with the intent of the Sandia Quality Assurance Program Plan (QAPP).

The mechanical excavation industry has evolved a number of empirical relationships between specific physical property tests and machine performance. Some of these tests have been standardized formally, and some have not. A few are nearly unique in their details to the manufacturer that favors them. The large amount of variability in the conditions encountered during rock excavation means that ultra-precise physical properties measurements are not needed or wanted. The reputation of any equipment manufacturer rests on the performance of their machines, so they have a strong interest in accurate, informative, yet efficient rock properties testing. The sole purpose of this report is to obtain those physical properties which the mechanical excavation industry is accustomed to using in the design of their products. The work discussed here is not intended to characterize or extend the database of proposed repository rock types, but only to enable determination of mechanical excavator performance estimates.

Task 1.1 of this project attempted to predict excavator performance on the basis of data already available within the YMP. A conclusion of that Task was that specific additional information was needed in order to produce reliable production and cost estimates for mechanical excavator performance in the welded tuffs of the NTS. The subtasks to gather the necessary information, which are presented and discussed in this SLTR, are the following:

- Thin-section petrographic analysis - The percentage of quartz and other abrasive minerals, the angularity of their grains, and the microstructure (pores, fractures) are best determined through thin-section petrologic analysis. Basic knowledge of mineralogic and microstructural characteristics allows good prediction of the wear to be expected on bits and cutters.

- Physical properties tests - A suite of physical properties tests commonly employed by the excavation industry was performed to provide data for mechanical excavator performance prediction:

  * Bulk density - Density affects the muck-handling properties of the excavator.

  * Uniaxial compressive strength - The compressive strength is one of several important parameters affecting rock excavatibility. The degree of its importance depends on many other factors, however.

  * Splitting tensile strength (Brazilian test) - The tensile strength indicates the toughness of the rock fabric.

  * Ultrasonic pulse velocities and dynamic elastic constants - Acoustic velocities, dynamic Young's modulus, and dynamic Poisson's ratio indicate the competency of the rock and its brittleness, which strongly affect its ease of excavation.

  * Cerchar abrasivity index (CAI) - This direct abrasion test gives a strong indication of the bit wear to be expected.

* Estimated abrasivity - The quartz content of the rock is a rough measure of the abrasiveness of the rock.

* Compressive to tensile strength ratio - This is an aggregate measure of the toughness of the rock fabric.

* Point load strength - The force-penetration behavior indicates the forces required to fail the rock.

* Punch strengths - This test uses indenters manufactured from excavator cutters and bits for a more exact determination of required cutter loads and indentations.

Each of these categories is discussed in detail in the following sections.

Samples of three occurrences of welded tuff were obtained from the NTS. These included 43 large rock pieces from the East Lower Test Pit at Fran Ridge, three small rock pieces from Busted Butte, and five 11 in. (28 cm) diameter cores from the G-Tunnel. These samples represent a range of welded tuff lithologies useful for predicting the performance of mechanical excavation systems at Yucca Mountain.

The rock samples from Busted Butte (per Sample Management Facility personnel) represent the TSw2 thermomechanical unit of the Topopah Spring Member of the Paintbrush Tuff (Ortiz et al, 1985), as do the Fran Ridge samples. This unit is being proposed for construction of a potential repository. The G-Tunnel cores are from the Grouse Canyon Formation at Rainier Mesa.

English units are used in this report, since they are the standard units used by mechanical excavator manufacturers in the United States. S.I. equivalents are provided (Appendix VII).

2.0 THIN-SECTION PETROGRAPHIC ANALYSIS

Hand samples or cores from each of the three locations were given to Dr. Robert Hutchinson of the Colorado School of Mines Geology Department for microscopic analysis of the rock composition and fabric. The reported percentages of components within the thin sections are visual estimates only. No quantitative mineralogic analysis was performed. The following discussion is a paraphrase of his report, which is included with this SLTR as Appendix VIII.

Examination of thin sections shows that tuff from the G-Tunnel is firmly compressed to the point of being welded, with strong compaction layering. The rock fabric consists of discoid pumice lapilli and volcanolithic fragments embedded in a submicroscopic ash matrix. The ash is compressed into subparallel planes bent locally around resistant crystal and lithic fragments. The matrix is devitrified, and partially silicified in some samples.

Mineralogically the G-Tunnel samples are made up of broken phenocrysts of sanidine feldspar and some plagioclase feldspar, compressed pumice lapilli, assorted lithic fragments, and cryptocrystalline volcanic ash of undetermined composition. Microcrystalline flakes and crystals of hematite are distributed throughout the matrix. The hematite gives the G-Tunnel samples their reddish color.

Tuff samples from all three locations are fresh and unweathered throughout. Fractured crystals are sharply angular and pumice lapilli are compressed and flattened with strong development of fiamme and axiolitic textures. Interstitial voids are rare in tuff from the G-Tunnel. Porosity values in those samples are controlled by the distribution of small vesicles within the lithic fragments, not within the pumice lapilli or the ash matrix. Lithophysae, more common in samples from Fran Ridge, also are present to a minor extent in the G-Tunnel samples. Microfractures also are absent from the G-Tunnel samples in thin section.

The Fran Ridge and the Busted Butte samples are similar to each other, as expected. The G-Tunnel samples have three times the amount of crystal fragments and pumice lapilli as the other two locations, with a proportionately lower volume of welded ash matrix. The porosity of the G-Tunnel samples appears higher, perhaps reflecting the greater average size of lithic fragments. No quantitative porosity measurements were made. The Fran Ridge and Busted Butte samples show a larger number of microcracks in the fabric, however (five to seven per thin section). The microcracks generally are oriented 60° to 75° to the compaction plane, range from 0.3 to 10 mm (0.01 to 0.39 in.) in length, and are filled with hematite or silica. In contrast to the G-Tunnel samples, which are highly compacted, the Fran Ridge and Busted Butte samples are moderately well-compacted, although just as completely devitrified. The devitrification phase has been followed by formation of quartz spherulites throughout the rock matrix, incorporating submicroscopic flakes of hematite. Some samples show a subsequent phase of silica- or calcite-filled veinlet formation.

Appendix VIII contains supplementary photomicrographs and a summary table of the findings from individual thin-sections.

3.0 PHYSICAL PROPERTIES

This section presents the density, uniaxial compressive strength, splitting tensile strength, ultrasonic pulse velocities, dynamic elastic constants, Cerchar abrasivity, point load strength, and punch strengths of samples of the tuffs.

Most of these tests were performed on cores drilled from the tuff samples (Figure 1) using diamond coring bits in a laboratory rotary drilling machine. Three specimens from each rock sample were used in most of the tests. The ultrasonic measurement, the uniaxial compressive strength test, and the Cerchar abrasivity determination used the same specimens since the ultrasonic measurement was nondestructive and the Cerchar abrasivity needed freshly broken pieces. A separate set of specimens was prepared for the

Figure 1. Sample YMP30 Coreholes

splitting tensile strength test. All cores were sawn and ground in accordance with the appropriate ASTM procedures (primarily ASTM D4543-85, along with the specific procedures for the tests, as described below). All specimens were tested at laboratory-ambient water content.

Average values of the physical properties of samples from each of the three locations are presented in Tables throughout this report. Appendix VI illustrates the same information in the form of plots showing average values and their 95% confidence limits. The physical property values determined for the individual samples tested at EMI are listed in Appendix III.

Samples from one of the G-Tunnel cores also were sent to seven mechanical excavator manufacturers and industry consultants. This was to add to the large body of data that has been collected for the Grouse Canyon tuff to allow comparison of mechanical excavator performance between the G-Tunnel and the proposed repository. The results of these additional determinations, where applicable, are included in the averages in the following Tables and the plots of Appendix VI. Appendix II includes a summary of these results as they apply to this report.

3.1 Bulk Density

The densities of all the prepared core specimens were calculated from measurements of their dimensions and their weight (Figure 2). The technique

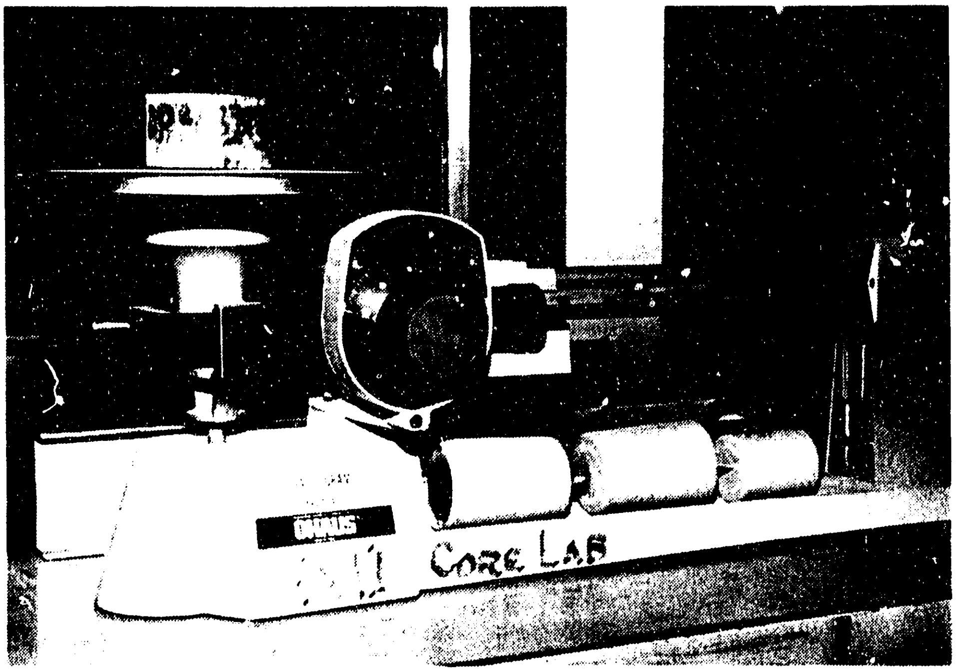

Figure 2. Weighing a Splitting Tensile Test Specimen

used was in accordance with ASTM D4543-85. Table 1 lists the resulting average bulk density values. Since the tuff samples had been exposed to the atmosphere for some time before arrival at EMI, all specimens were tested at room-dry moisture condition.

Table 1

Average Tuff Densities For Excavator Performance Prediction

tuff origin	avg / std dev density (lb/ft^3)	avg / std dev density (g/cm^3)	number of tests
Fran Ridge	144.9 / 4.4	2.32 / 0.07	21
Busted Butte	144.0 / 0.8	2.31 / 0.01	6
G-Tunnel	143.5 / 1.9	2.29 / 0.03	16

3.2 Uniaxial Compressive Strength

Uniaxial compressive strength determinations were performed in accordance with ASTM D2938-86. The results are summarized in Table 2. Core samples were sawn and ground (Figure 3) so that their length-to-diameter (L/D) ratios were approximately 2. These cores then were placed in a Soiltest compression machine (maximum load 250000 lbs, or 1.11 MN, Figure 4) where axial load was measured by gages in the hydraulic system. A preload of approximately 700 - 1000 lbs (3 to 4.5 kN) was applied before the load was ramped up at approximately 3450 lb/s (15.3 kN/s) until failure, which occurred in about 20 seconds. The major fragments were gathered and stored (Figure 5) for the Cerchar abrasivity determination described in Section 3.5.

Table 2

Average Tuff Uniaxial Compressive Strength

tuff origin	corrected avg / std dev compr. strength (psi)	corrected avg / std dev compr. strength (MPa)	number of tests
Fran Ridge	15000 / 6090	103.7 / 42.0	21
Busted Butte	20600 / 10900	142.2 / 75.4	6
G-Tunnel	15700 / 7160	108.1 / 49.3	24

As-measured specimen strength was the failure load divided by the cross sectional area of the core. To ensure unbiased comparison of the strength values, they were corrected to the equivalent strengths of samples with L/D ratios of exactly 2.0. This was done using the following standard equation specified by ASTM D2938-86:

$$C = C_a / (0.88 + 0.24 * (D / L))$$

where: C = compressive strength of an equivalent L/D = 2 specimen
C_a = measured compressive strength of specimen of length L and diameter D

The cores prepared by EMI were drilled at various angles to the plane of compaction of the tuff (Appendix III). To determine whether core orientation affected the strength results, hypothesis testing of a regression model was performed on the data grouped according to sample origin (Appendix V). In all three cases, the uniaxial compressive strength of the cores was concluded to have been unaffected by the visible anisotropy of the tuff fabric at the 95% level of confidence.

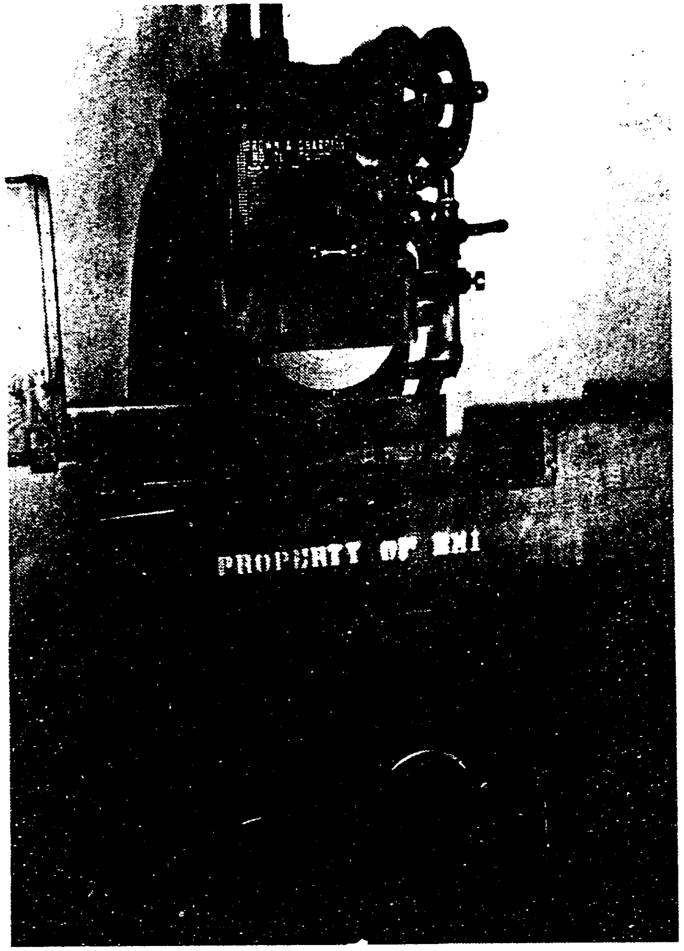

Figure 3. EMI Core Grinding Setup

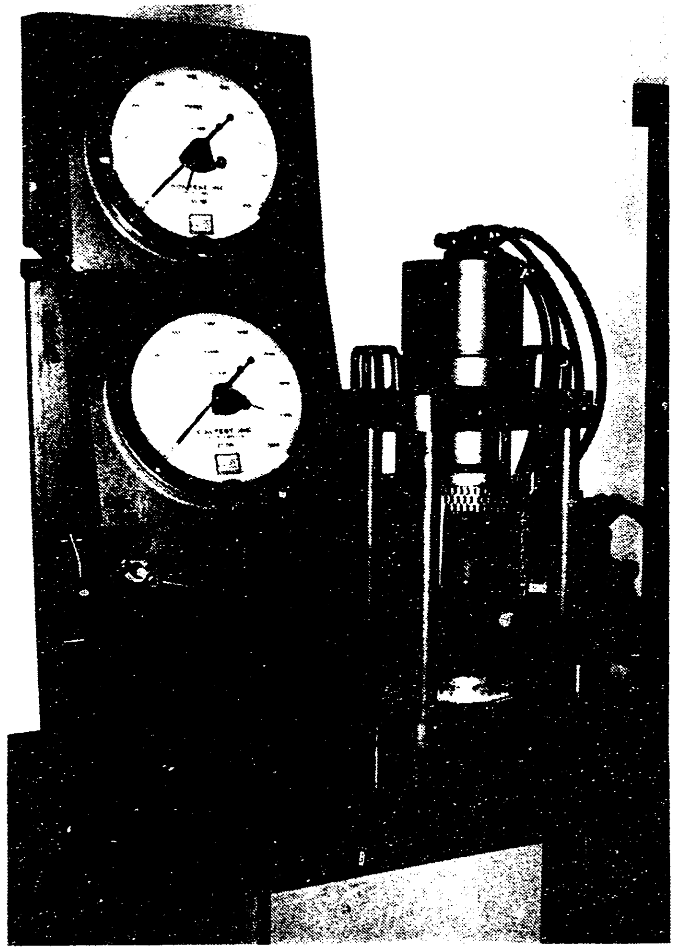

Figure 4. EMI Compression Test Machine

Figure 5. Saving Test Specimen Fragments For CAI Determination

3.3 Splitting Tensile Strength

Core sample preparation for the splitting tensile strength testswas similar to that for the uniaxial compressive strength tests,except that the L/D ratios were approximately 0.5. Theprocedures recommended in ASTM D3967-86 were followed. The load at failure was converted to splitting tensile strength (also known as indirect tensile strength) with the equation:

$$S = 2 * P / (pi * L * D)$$

where: S - splitting tensile strength
P - failure load
pi - the mathematical constant (3.1416)

The test results are shown in Table 3. Figure 6 shows a sample set up and ready to test in the Soiltest machine.

Load was applied along core diameters at a variety of angles to the plane of compaction of the tuff (Appendix III). The relationship between load orientation and splitting tensile strength was evaluated as described in Appendix V. No effect was discerned at the 95% level of confidence.

Table 3

Average Tuff Splitting Tensile Strength

tuff origin	avg / std dev tensile strength (psi)	avg / std dev tensile strength (MPa)	number of tests
Fran Ridge	2160 / 452	14.9 / 3.1	22
Busted Butte	2490 / 537	17.1 / 3.7	6
G-Tunnel	1490 / 316	10.2 / 2.2	10

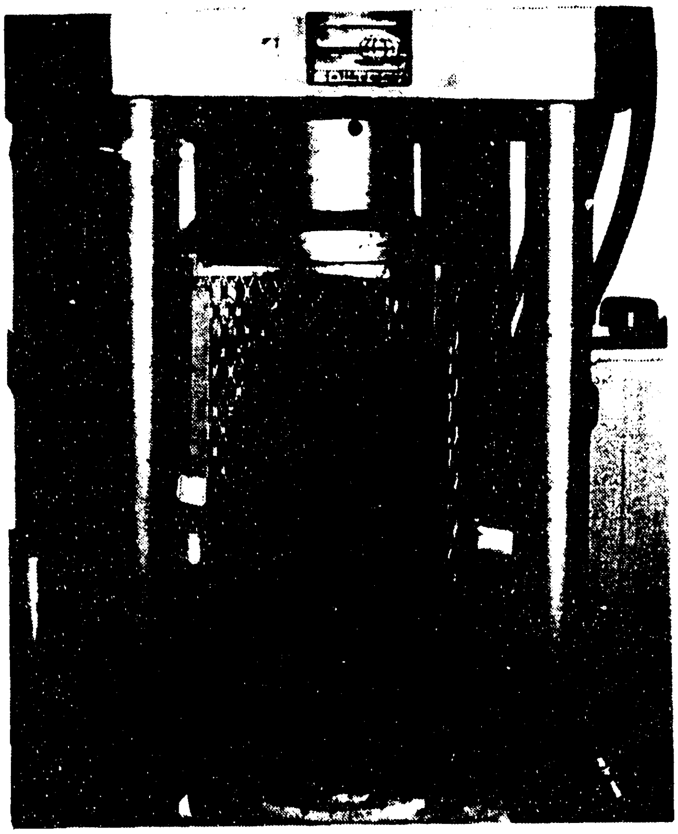

Figure 6. Splitting Tensile Strength Test Ready to Begin

3.4 Ultrasonic Pulse Velocities and Dynamic Elastic Constants

Ultrasonic pulse velocities and dynamic elastic constants were measured in the L/D = 2 core samples before they were destroyed in the uniaxial compressive strength tests (Figure 7). The instrument setup followed the guidelines set forth in ASTM D2845-83, with a pulse generator feeding a 500 Hz rectangular wave (duration 10 microseconds) both to a digital oscilloscope and to a shear wave transducer cemented to the sample. The coupling medium was phenyl salicylate. After traveling through the sample, the signal was received by a second transducer, amplified, and fed into the second channel of the oscilloscope. The oscilloscope display showed both signals simultaneously. Thus the time that had elapsed between the original signal pulse and the arrival of the attenuated pulse through the rock was readily visible. The arrivals of both the P-wave and the S-wave were noted and used to calculate pulse velocities (Table 4) according to the specified procedure in ASTM D2845-83.

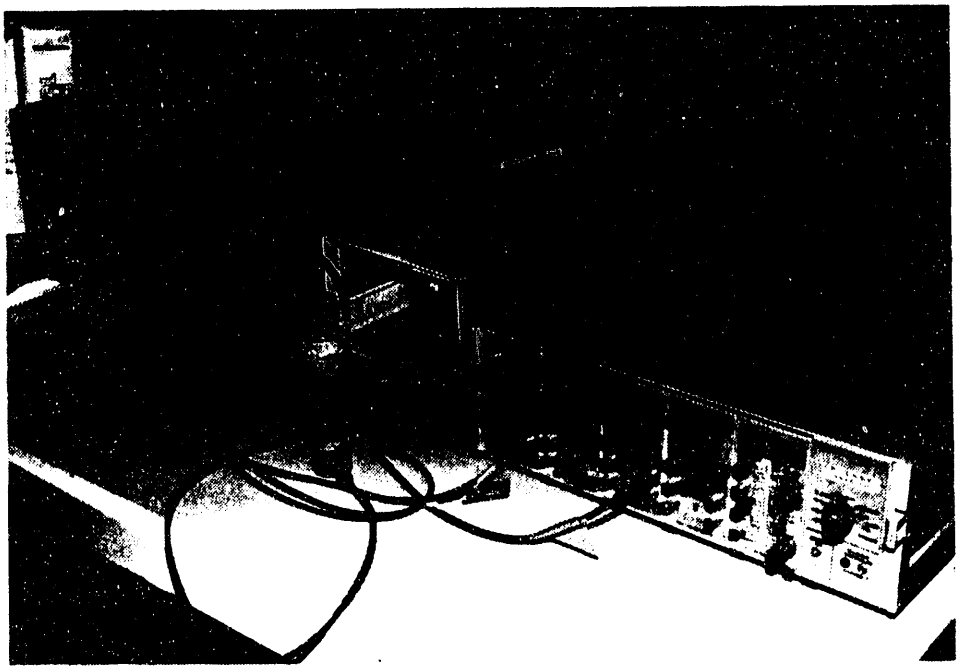

Figure 7. EMI Ultrasonic Pulse Measurement Setup

The possible effects of fabric anisotropy on the results of the ultrasonic measurements were evaluated as described in Appendix V. No relationship was shown at the 95% level of confidence.

Values of dynamic Young's modulus and Poisson's ratio were calculated from the ultrasonic pulse velocities as specified in ASTM D2845-83 (Table 5).

Table 4

Average Tuff Ultrasonic Pulse Velocities

tuff origin	avg / std dev P-wave velocity (ft/s)	(m/s)	avg / std dev S-wave velocity (ft/s)	(m/s)	number tests
Fran Ridge	14700 / 485	4480 / 148	9440 / 529	2876 / 161	21
Busted Butte	14700 / 203	4492 / 62	9980 / 176	3042 / 54	6
G-Tunnel	13800 / 380	4202 / 116	8700 / 244	2653 / 74	9

Table 5

Average Tuff Dynamic Elastic Constants

tuff origin	avg / std dev Young's modulus (10^6 psi)	(GPa)	avg / std dev Poisson's ratio	number of tests
Fran Ridge	6.35 / 0.54	43.8 / 3.7	0.16 / 0.05	18
Busted Butte	6.65 / 0.17	45.9 / 1.2	0.07 / 0.04	6
G-Tunnel	5.46 / 0.31	37.6 / 2.1	0.17 / 0.02	9

This was done if less than 6% variation was evident in the P-wave travel times of the three specimens from a given rock sample. All rock samples tested except one satisfied this condition. The equations were:

$$E = \frac{d * V_s^2 * \left(3 * V_p^2 - 4 * V_s^2\right)}{\left(V_p^2 - V_s^2\right)}$$

and:

$$u = \frac{\left(V_p^2 - 2 * V_s^2\right)}{2 * \left(V_p^2 - V_s^2\right)}$$

where: E = Young's modulus
V_s = S-wave travel time
V_p = P-wave travel time

d = sample density
u = Poisson's ratio

The static Young's modulus of a single G-Tunnel core sample was determined by measuring the axial deformation during a uniaxial compressive strength test. The slope of the stress-strain curve, both tangent and secant, was 1.33×10^6 psi (9.2 GPa).

3.5 Cerchar Abrasivity Index

The major fragments remaining after the uniaxial compression tests were retained and used to find the Cerchar Abrasivity Index (CAI). The CAI was determined from the abrasion of five metal pins after they each were dragged across a freshly broken rock surface under controlled conditions. The pins were fabricated of heat-treated steel with a tensile strength of 29 kpsi (200 MPa). Each pin was sharpened into a 90° cone and locked into the 15 lb (7 kg) weighted head of the test fixture, while the rock sample was clamped in the vise with the freshly broken surface facing upward (Figure 8A). The fixture head was lowered carefully until the sharpened point contacted the rock surface, then the head was pulled sideways for a distance of 0.4 in. (1 cm) across the rock surface in one second (Figure 8B). The pin then was removed from the weighted head and its tip was examined under a microscope (Figure 9). Two perpendicular diameters of the abraded area on the tip were measured. The average of the ten reading s (two per each of five pins), converted to tenths of millimeters, was the CAI for the specimen. Where there was noticeable planar structure in the rock, as in all the welded tuff samples, two of the pins were scratched parallel to the structure plane and three were scratched perpendicular to it. The average CAI's for the samples from the three locations are listed in Table 6.

3.6 Estimated Abrasivity

Rock abrasivity was estimated in several ways, all involving the volumetric mineralogic composition of the tuff. The basic premise was that the more hard, abrasive minerals contained in the rock (particularly quartz), the more wear experienced by mechanical cutters.

One sample of G-Tunnel tuff was examined with an optical microscope to categorize the mineral content of the rock into three groups according to Mohs hardness:

1. Mohs hardness less than 4: 10%
2. Mohs hardness 5 to 6: 60%
3. Mohs hardness 7: 30%

The mineralogic content of six other samples of G-Tunnel tuff was determined by handlens examination: the quartz volume fraction varied from 25% to 72%, with an overall average of 42% (Appendix II).

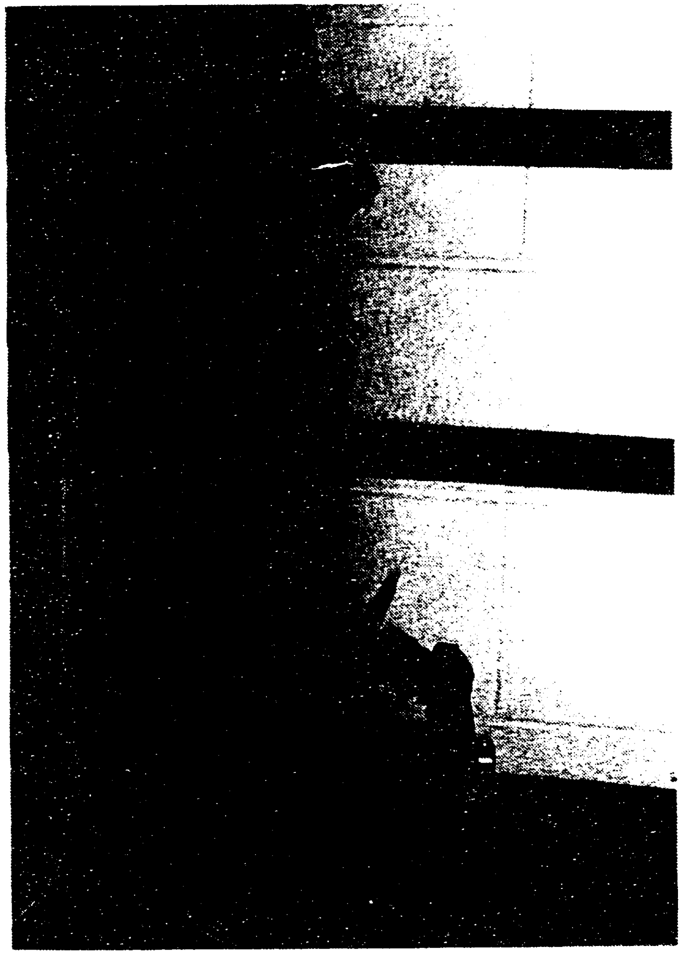

Figure 8A. CAI Test Ready to Begin

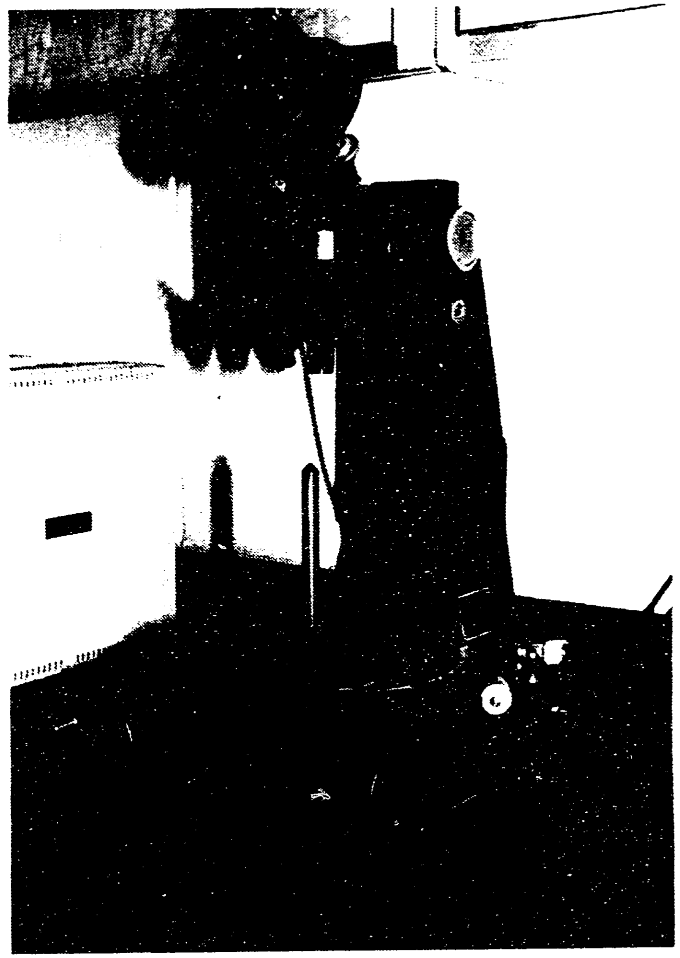

Figure 9. Abraded Cerchar Pin Being Examined Under Microscope

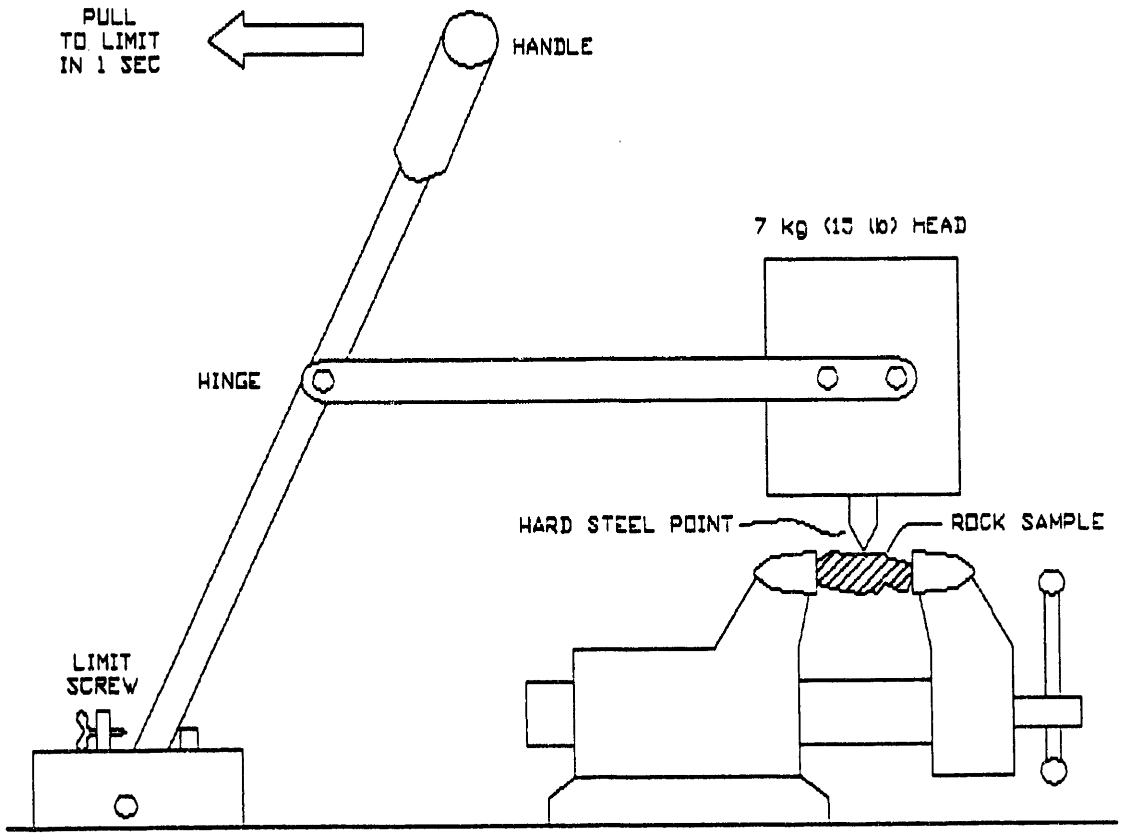

Figure 8B. Schematic Diagram of CAI Test Apparatus in Use

Table 6

Average Tuff Cerchar Abrasivity Index (CAI) Values

tuff origin	avg / std dev CAI	number of tests
Fran Ridge	4.39 / 0.61	21
Busted Butte	4.48 / 0.74	6
G-Tunnel	4.36 / 0.43	14

3.7 Compressive to Tensile Strength Ratio

The ratio of compressive to tensile strengths gave another indication of the toughness of the rock fabric. Since the compressive and tensile strengths were not determined from the same specimens and could not be matched one-for-one, this ratio was calculated from the average strength values for each of the three sample groups. For this reason, standard deviations are not available. Table 7 lists the values of this ratio.

Table 7

Average Tuff Compressive to Tensile Strength Ratios

tuff origin	avg strength ratio	number of tests (compr/tensile)
Fran Ridge	7.0	21/22
Busted Butte	8.3	6/6
G-Tunnel	10.6	24/10

3.8 Point Load Test

The point load test and the punch tests discussed in the following sections were performed on samples of tuff from the G-Tunnel. The main purpose was to add to the information collected from the previous use of mechanical excavators there.

Specimens from the G-Tunnel samples were prepared for the point load tests in accordance with accepted procedure as outlined in Broch and Franklin (1972), with the exception that the cores had a smaller diameter (1.0 in. or 2.5 cm). The test apparatus consisted of two conical platens with spherical tips of 0.125 in. (0.3175 cm) radius, driven by a small hand-operated hydraulic press (Figure 10). For a test, the core was placed so the load applied by the tips acted along a core diameter. The load at failure was divided by the square of the sample diameter to obtain the point load index, which then was corrected to the point load index for the standard size of core through the use of figure 25 in Broch and Franklin (reproduced in Appendix IV). Point load strengths were back-calculated from the standard-size point load indices, and are listed in Table 8.

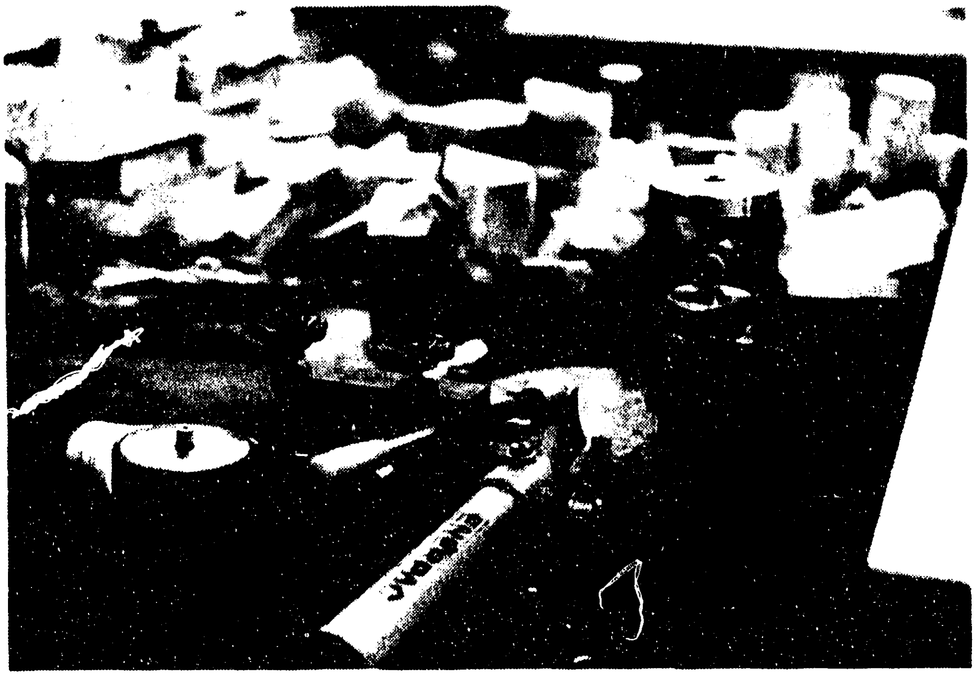

Figure 10. Point Load Test Ready to Begin

Table 8

Point Load Strengths For Three Specimens From the G-Tunnel. Orientation is in relation to the plane of compaction of the tuff.

load orientation	point load strength (psi)	(MPa)	number of tests
perpendicular	1070	7.38	1
perpendicular	1070	7.38	1
parallel	1230	8.48	1

3.9 Punch Test - Spherical Indenter

This nonstandard test was developed to model actual boring conditions. It was performed on four tuff pieces from the G-Tunnel using a Riehle testing machine (200000 lb or 890 kN maximum capacity). A conical tungsten-carbide button was pressed into sawcut sample surfaces that had been confined by casting them with Hydrostone inside 4 in. (10 cm) diameter by 5 in. (13 cm) high steel cylinders (Figures 11 through 15). The displacement of the test button into a sample and the applied load were monitored by a Temposonics linear displacement transducer and by a pressure cell on the hydraulic line, respectively. The output signals from these devices were fed into a Compaq Deskpro 286 computer equipped with a MetraByte Dash 16 data acquisition and control interface board. The data were stored on magnetic disk for analysis. Data curves were plotted showing the relationship between the force and the penetration during testing.

As shown in Figures 16 through 20, loads greater than 40000 lbs (178 kN) and penetrations greater than 0.15 in. (0.4 cm) occurred before chips formed in the tuff samples from the G-Tunnel.

3.10 Punch Test - Cutter Section Indenters

In this brief series of punch tests, again on samples from the G-Tunnel, sections of a disk cutter were substituted in the platens of the Riehle test machine for the conical tungsten-carbide button described above. Two types of 17 in. (43 cm) diameter disk cutters were used in these tests: a 60° wedge cutter (Figures 21 through 23) and a constant cross section cutter (Figures 24 and 25). Two samples (one per cutter section) were prepared as for the spherical indenter punch test described above. The experimental setup also was the same.

The wedge cutter section applied over 100,000 lbs (445 kN) of force and penetrated 0.3 in. (0.8 cm) before the entire sample face spalled off. The constant cross section cutter section, on a widely spaced cut, applied over 200,000 lbs (890 kN) of force and penetrated more than 0.6 in. (1.5 cm) before the sample failed.

4.0 DISCUSSION OF RESULTS

The bulk density, uniaxial compressive strength, and splitting tensile strength values are within the ranges presented in previous work (see bibliography in SLTR90-7003). This assures the continuity of the information presented in this report with that in other references. Table 9 illustrates these parameters for other rock types that have been tested for mechanical boreability.

Young's modulus and Poisson's ratio for several other rock types are listed in Table 10.

Figure 11. G-Tunnel Samples Cast in Hydrostone For Punch Tests

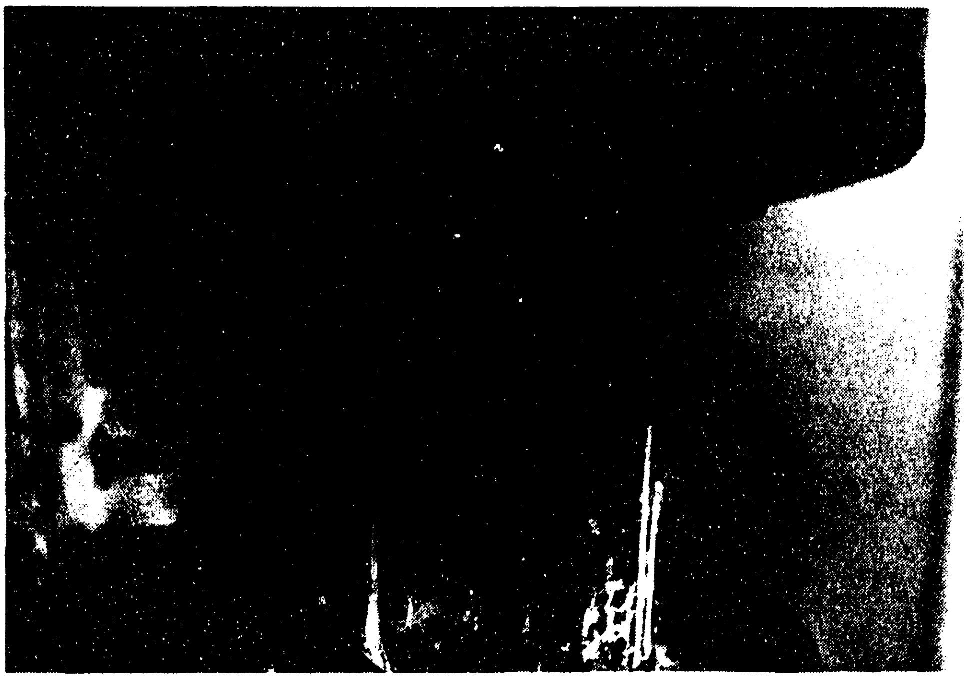

Figure 12. Spherical Indenter Punch Test Ready to Begin

Figure 13. Crushing the Rock Below the Indenter

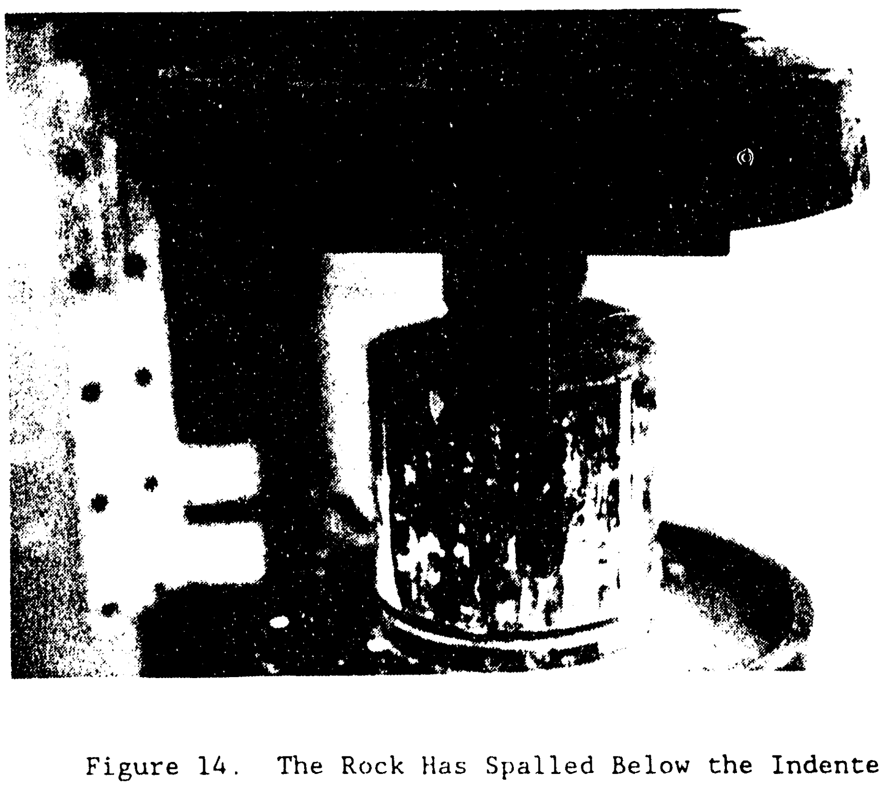

Figure 14. The Rock Has Spalled Below the Indenter

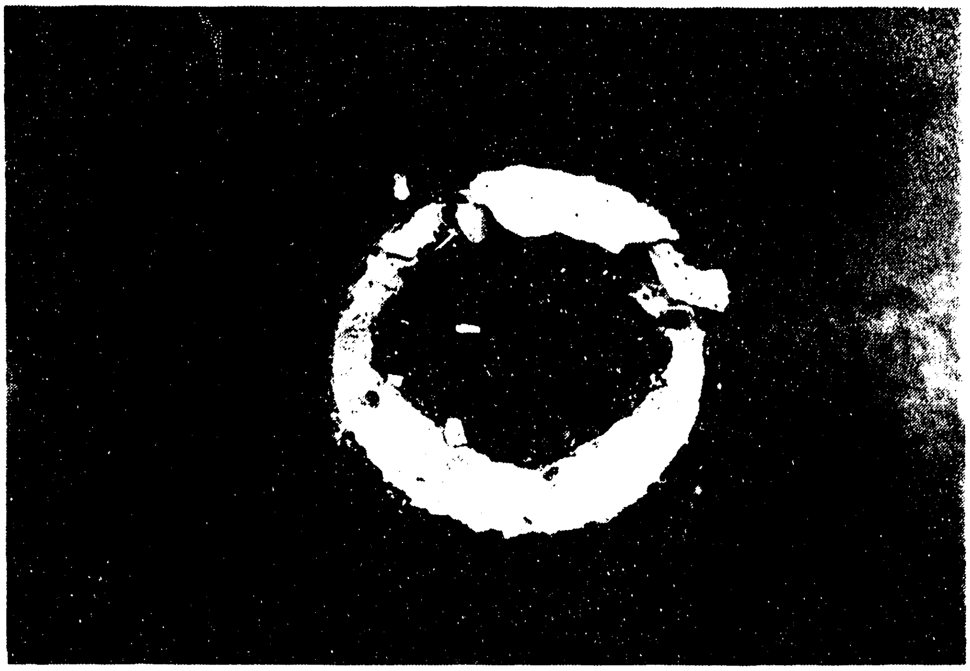

Figure 15. Closeup of Failed G-tunnel Specimen After Load of 40,000 lbs (178 kN) and Indentation of 0.15 in. (0.38 cm) Using the Spherical Indenter

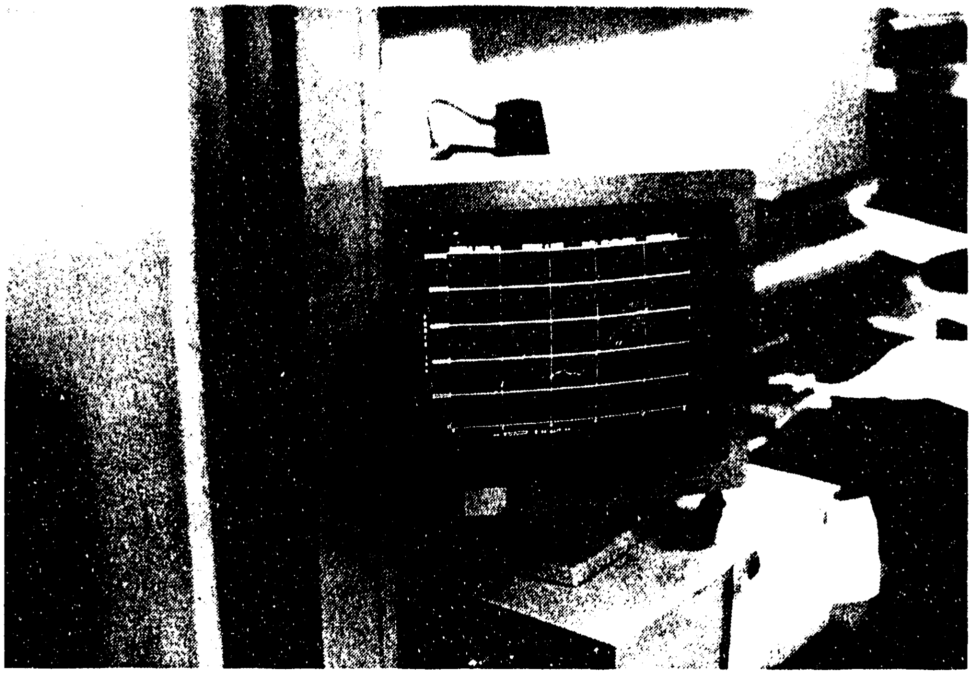

Figure 16. Realtime Force-penetration Curve During Testing

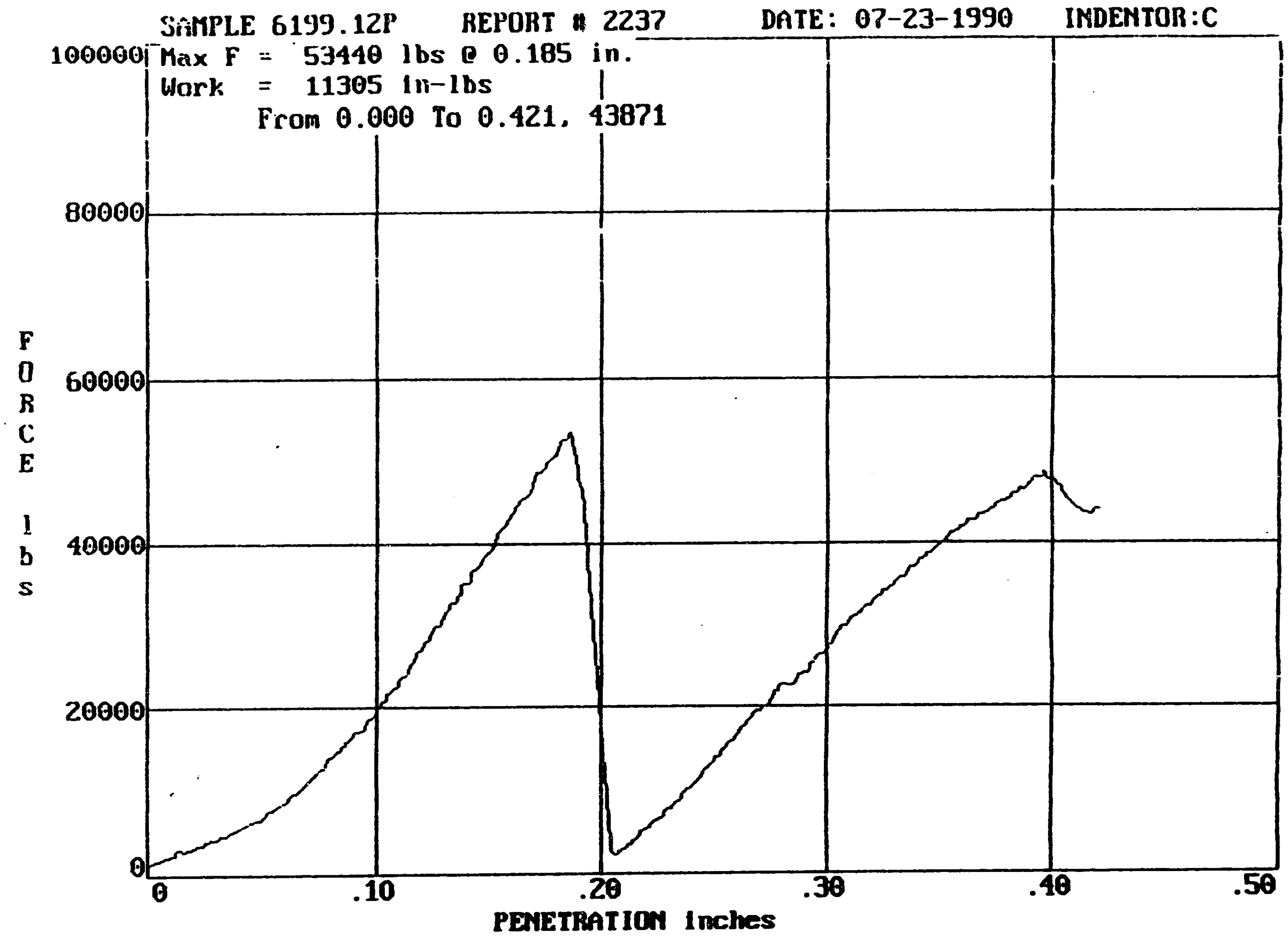

Figure 17. Force-penetration Curve, Spherical Indenter, G-Tunnel Tuff

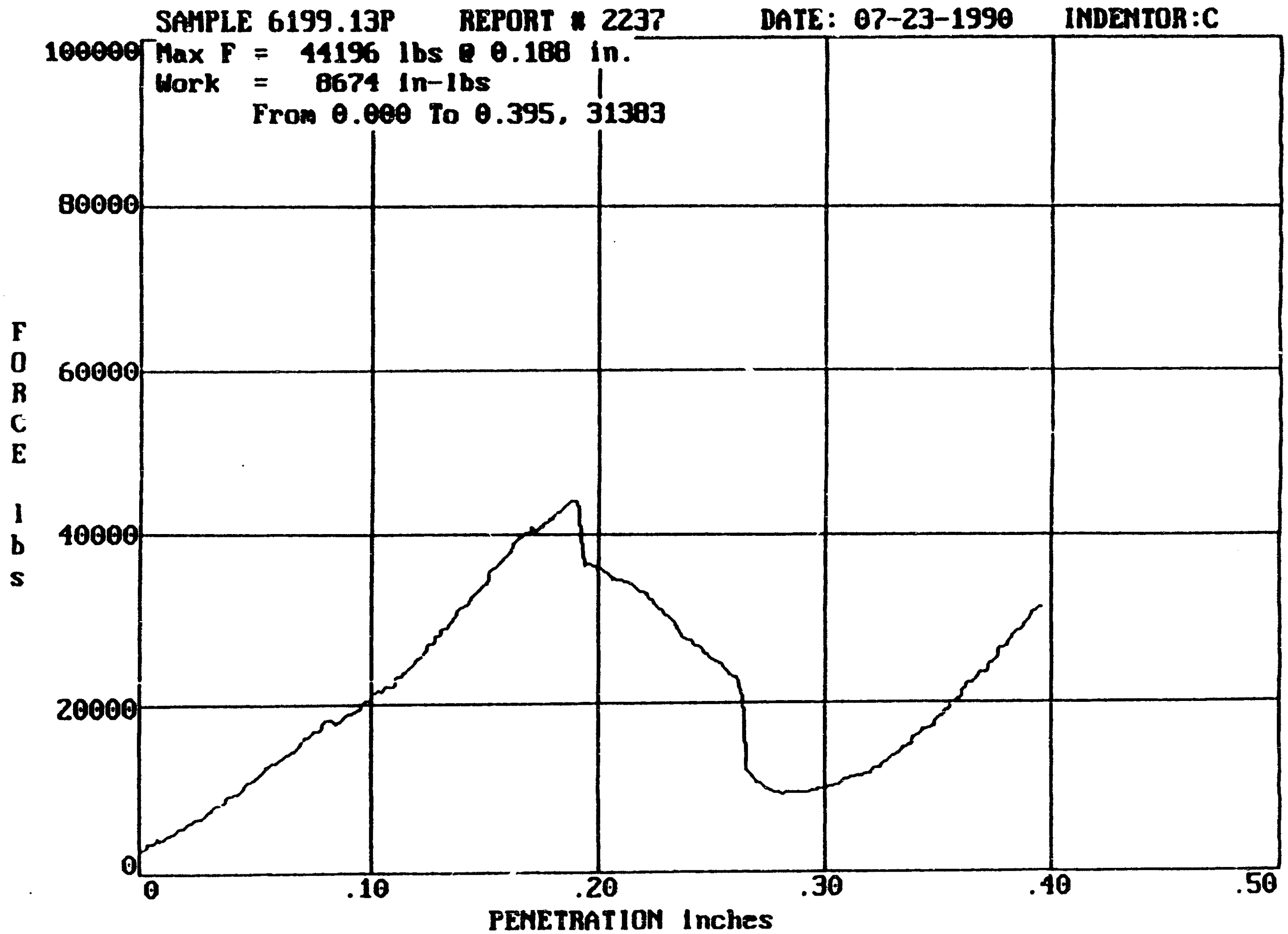

Figure 18. Force-penetration Curve, Spherical Indenter, G-Tunnel Tuff

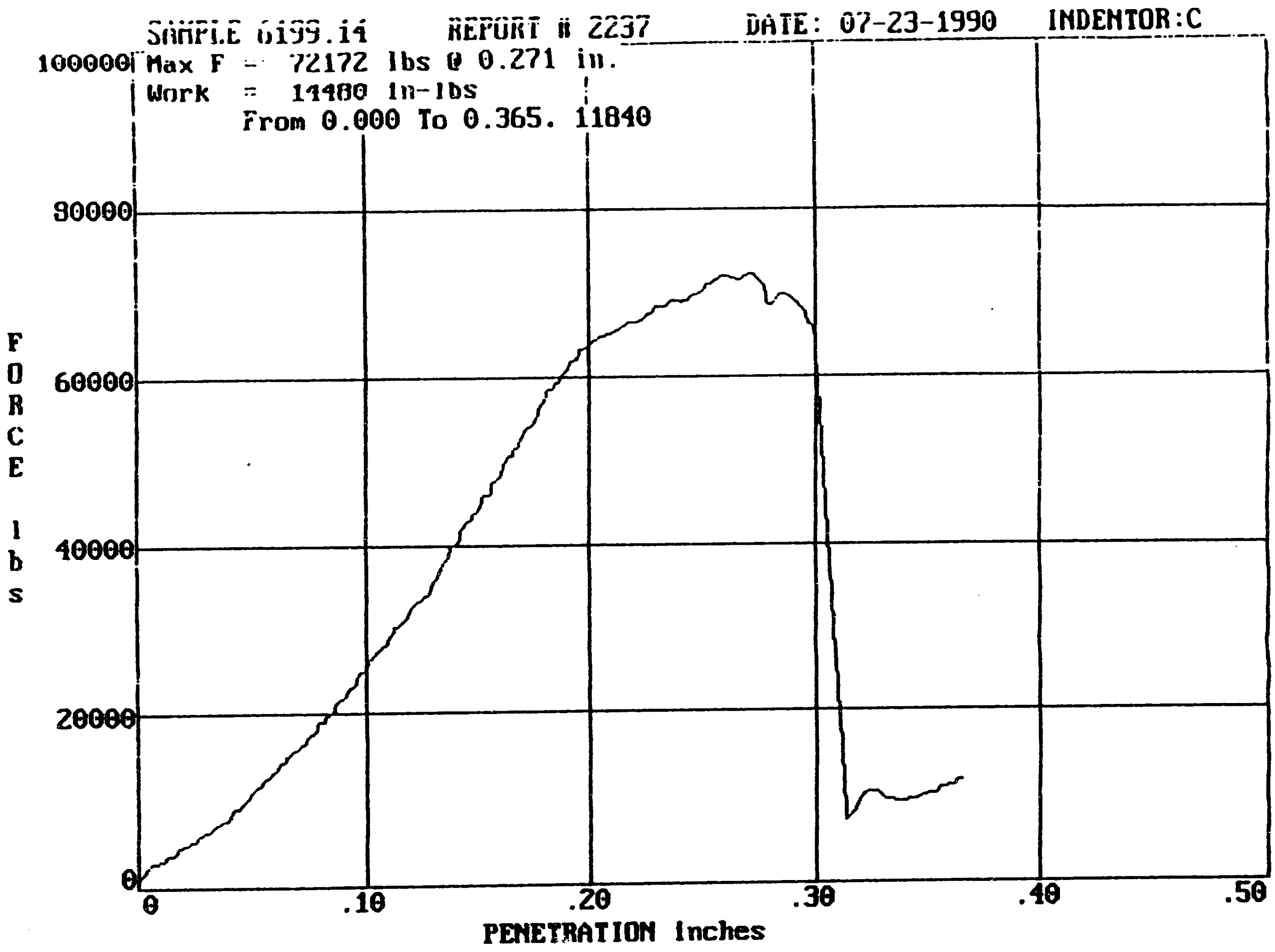

Figure 19. Force-penetration Curve, Spherical Indenter, G-Tunnel Tuff

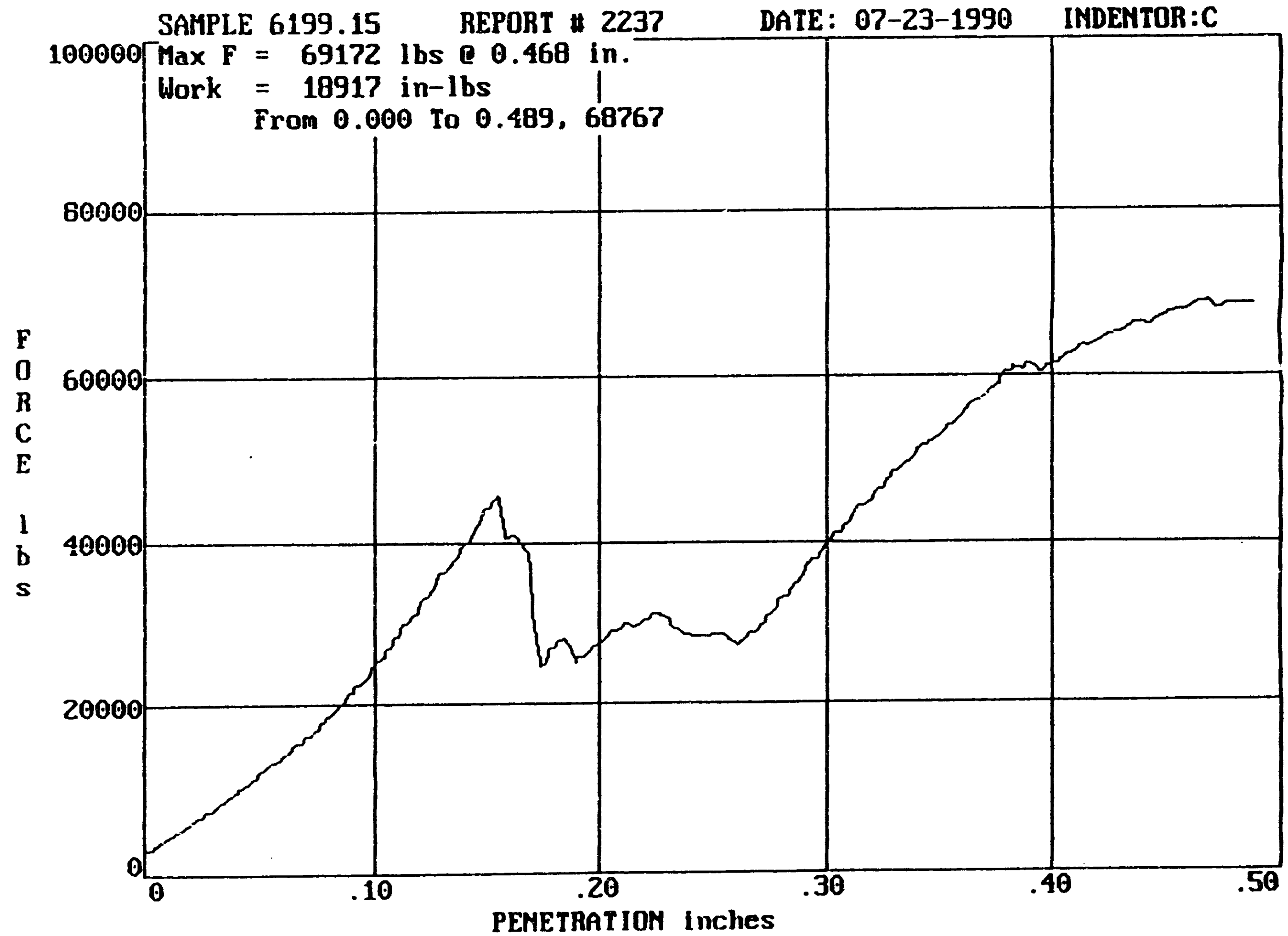

Figure 20. Force-penetration Curve, Spherical Indenter, G-Tunnel Tuff

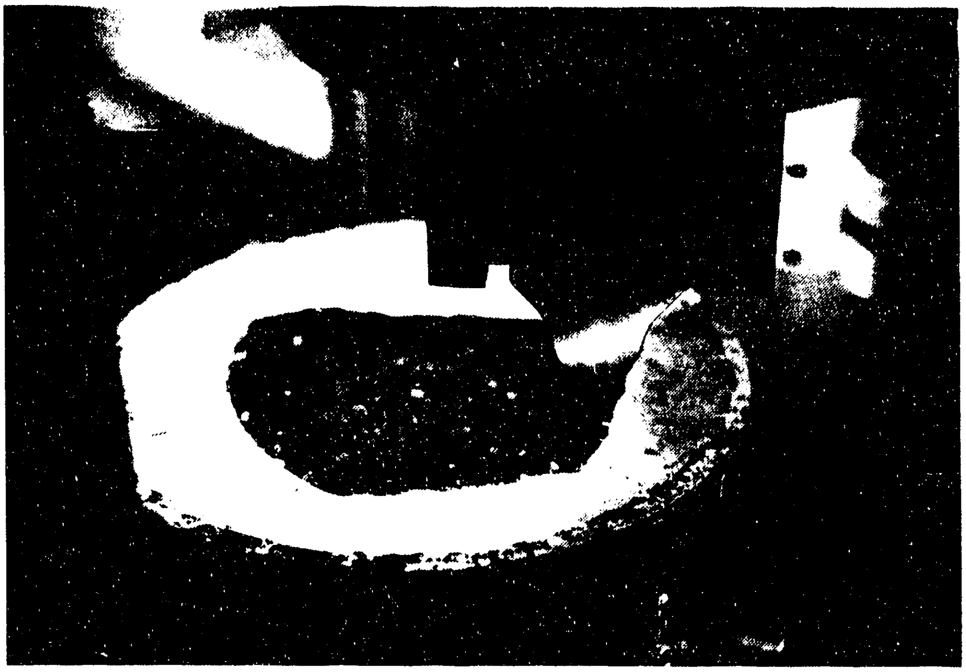

Figure 21. 60 Degree Wedge Cutter Punch Test Ready to Begin

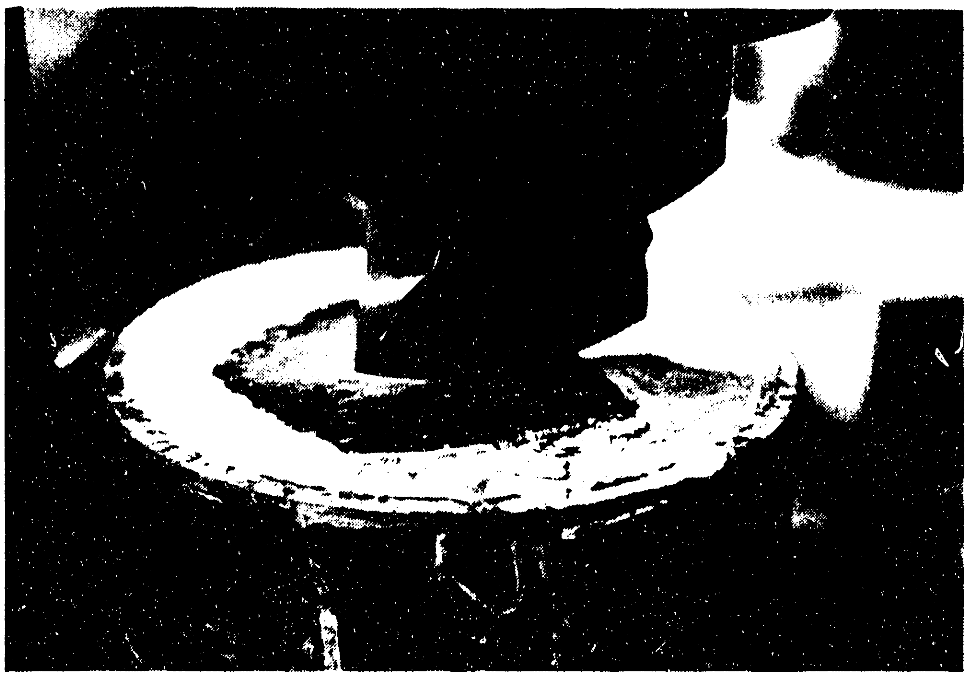

Figure 22. Angle View of 60 Degree Wedge Cutter Indenter

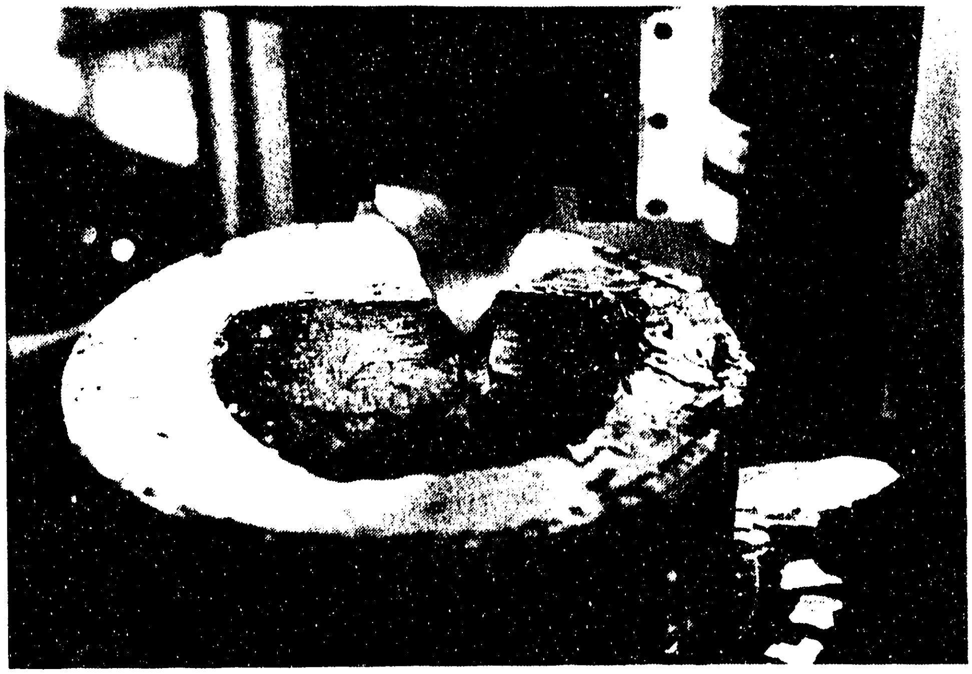

Figure 23. Closeup of Failed G-Tunnel Specimen After Load of 100,000 lbs (445 kN) and Indentation of 0.3 in. (0.8 cm) Using the 60 Degree Wedge Cutter Indenter

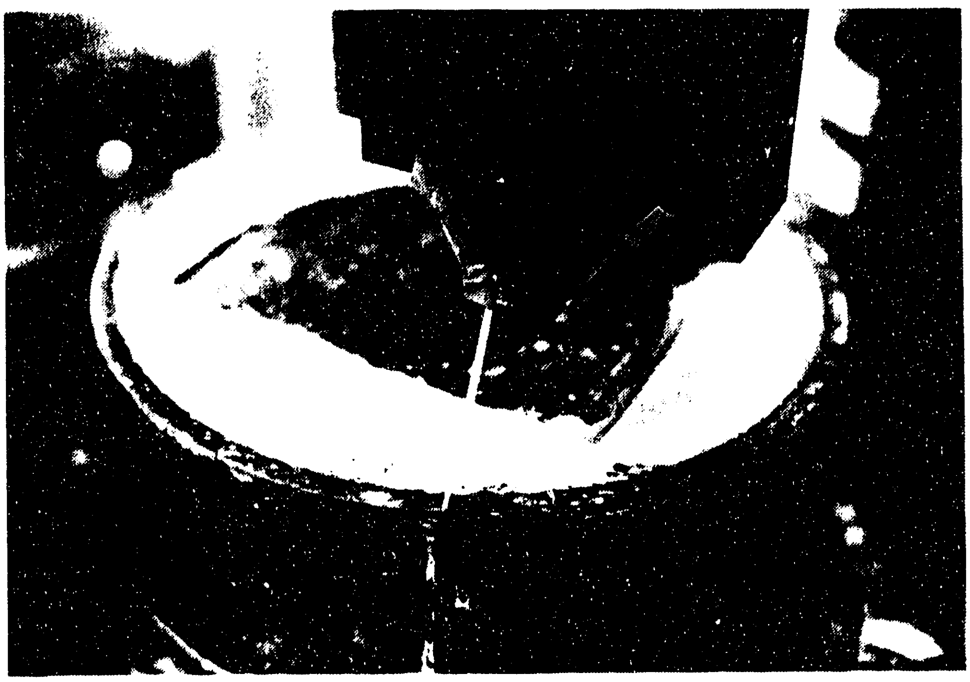

Figure 24. Constant Cross Section Cutter Punch Test Ready to Begin

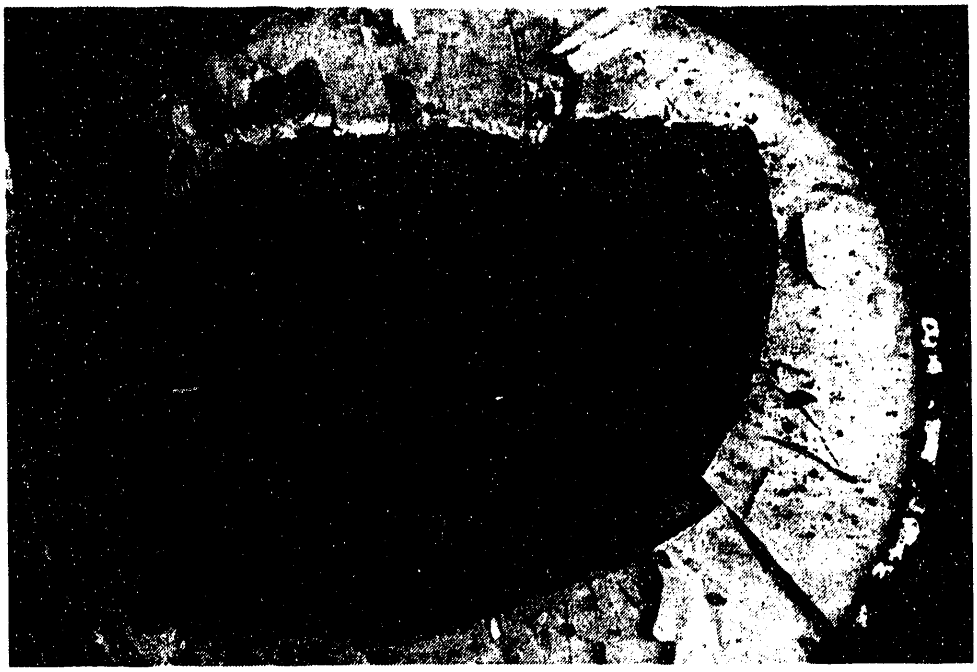

Figure 25. Completed Constant Cross Section Cutter Punch Test

The CAI values reported here are consistent with moderately high quartz and feldspar content and are equivalent to values measured for moderately hard metamorphic rocks (Table 11). Note that rocks with CAI values of 4.5 are three times more abrasive than rocks with CAI values of 1.5.

The ratios of compressive to tensile strengths for all three sample groups were rather low in relation to measurements of other rock types (Goodman, 1980). However, they were similar to measurements for rocks from the NTS, including granite, basalt, and tuff (12.1, 11.3, and 10, respectively). Most rocks vary between 20 and 60, although the ratio for Flaming Gorge shale has been measured at 168 and a mica schist loaded perpendicular to the schistosity produced a ratio of 100. There is no clear relationship between compressive to tensile strength ratio and rock type.

The penetrations of the spherical indenter and the cutter section indenters into the G-Tunnel samples were noticeably greater than most brittle rocks require for failure. Such large penetrations usually indicate a fairly ductile rock that does not fracture well. However, upon reaching these penetrations, the indenters caused good chip formation. The Grouse Canyon tuff may require that the boring machine exceed some critical penetration for efficient rock breakage.

Table 9

Density, Uniaxial Compressive Strength, and Splitting Tensile Strength From Previous Mechanical Boreability Studies (Ozdemir et al., 1983; Ozdemir and Miller, 1986; Carmichael, 1989; Ozdemir et al., 1973)

rock type	density (g/cm^3)	uniaxial compressive strength (psi)	uniaxial compressive strength (MPa)	splitting tensile strength (psi)	splitting tensile strength (MPa)
oil shale	2.16	10876	75.0	1032	7.1
Dakota Sandstone	2.18	7468	51.5	561	3.9
Berea Sandstone	2.24	9774	67.4	542	3.7
Indiana Limestone	2.61	12170	83.9	1202	8.3
Holston Limestone	2.70	17213	118.7	900	6.2
Precambrian granite	2.7	20000	138	1700	12
Granodiorite	2.7	32000	221	1900	13
Doleritic basalt	2.89	27400	189	2180	15
Non-amygdaloidal basalt	----	14200	98	1900	13
Mod-amygdaloidal basalt	----	13300	92	1700	12
Highly-amygdaloidal basalt	----	16200	112	1160	8

Table 10

Young's Modulus and Poisson's Ratio Values From Previous Mechanical Boreability Studies (Ozdemir et al., 1983; Ozdemir and Miller, 1986; Ozdemir et al., 1973)

rock type	Young's modulus (10^6 psi)	Young's modulus (GPa)	Poisson's ratio
oil shale	2.17	15.0	0.30
Dakota Sandstone	3.0	20.7	0.14
Berea Sandstone	3.8	26.2	0.18
Indiana Limestone	6.4	44.1	0.21
Holston Limestone	10.6	73.1	0.27
Precambrian granite	7.0	48.3	----
Granodiorite	10.3	71.0	----

Table 11

Cerchar Abrasivity Index Values From Previous Mechanical Boreability Studies (Ozdemir and Miller, 1986)

rock type	CAI
Dakota Sandstone	0.5 - 3.0 (avg = 1.6)
Berea Sandstone	0.5
Indiana Limestone	1.2
Holston Limestone	1.3
shale	0.9 - 1.1

5.0 CONCLUSIONS

The purpose of this SLTR was to report the results of particular physical property tests chosen for their utility for predicting the performance of mechanical excavation systems. Additional tests were performed to ascertain the reproducibility of the data provided in previously-published work, which were used for preliminary, order-of-magnitude predictions reported in SLTR90-7003. A SAND report will be written summarizing these two SLTRs and giving the results of a second round of performance predictions that will utilize the physical data reported here.

The ultimate goal of this multi-tasked project (SNL contract #35-0039) is to recommend boring machine designs and/or modifications for use at the Yucca Mountain site. This study is not meant solely to add to the large amount of geotechnical data already collected; it is meant to provide the information that performance predictors and excavation equipment manufacturers need for their work.

The impacts of particular test results on the performances predicted for various mechanical excavators will vary with the type of excavator and with the effects of the other physical properties. Machine design parameters and rock mass properties are inter dependent. Performance prediction is based on a number of empirical relationships. The effects of the physical properties reported here on the production rates of various machines will be discussed in the concluding SAND report for this Task.

6.0 REFERENCES

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U.S. Dept. of Energy, 1989. The Yucca Mountain Project Reference Information Base, Version 4, released February 1, 1989, document number YMP/CC-0002. (NNA.890330.0077)

APPENDIX I

Information from the Reference Information Base Used in this Report

This report contains no information from the Reference Information Base.

**Candidate Information
for the
Reference Information Base**

This report contains no candidate information for the Reference Information Base.

**Candidate Information
for the
Site & Engineering Properties Data Base**

This report contains no candidate information for the Site and Engineering Properties Data Base.

APPENDIX II

This appendix summarizes the reports from Anderson Strathclyde PLC, Atlas Copco/Eickhoff, Dosco Overseas Engineering, Paurat GmbH, Voest-Alpine, Westfalia Lunen, and J. E. Friant & Associates on the results of their investigations. Note that they were sent samples only of the G-Tunnel tuff. The main purpose of this part of the program was to add to the information collected from the previous use of mechanical excavators in the G-Tunnel.

SANDIA YMP PROJECT
PHYSICAL PROPERTY TEST RESULTS
EARTH MECHANICS INSTITUTE

SAMPLE NUMBER (full)	DENSITY (lb/ft^3)	L/D RATIO	P-WAVE VELOCITY (ft/sec)	S-WAVE VELOCITY (ft/sec)	YOUNGS MOD (E6 psi)	POISSON RATIO	EQUIV L/D=2 STRENGTH (psi)	COMPRES LOAD ANGLE (deg)	TENSILE STRENGTH (psi)	TENSILE LOAD ANGLE (deg)	CAI
FRELTP-0m-3m-3-SNL/CSM	141.5	2.11	13421	9320	5.49	0.03	11377	15	---	---	4.09
"	145.1	2.14	14581	10480	6.65	-0.03	23825	0	---	---	3.92
"	144.2	2.19	14448	9774	6.41	0.08	21284	0	---	---	3.78
"	144.7	0.53	---	---	---	---	---	---	1691	0	---
"	144.9	0.49	---	---	---	---	---	---	1654	0	---
"	144.3	0.52	---	---	---	---	---	---	2747	0	---
"	141.7	0.51	---	---	---	---	---	---	2202	0	---
FRELTP-0m-3m-4-SNL/CSM	144.1	2.17	14582	9821	6.51	0.08	15447	75	---	---	3.63
"	144.8	2.18	15436	9870	7.03	0.15	15719	80	---	---	4.38
"	142.9	2.20	14850	8662	5.76	0.24	9326	90	---	---	4.37
"	146.4	0.56	---	---	---	---	---	---	2658	20	---
"	141.9	0.54	---	---	---	---	---	---	1774	0	---
"	144.9	0.55	---	---	---	---	---	---	2619	0	---
FRELTP-0m-3m-5-SNL/CSM	140.7	2.16	14393	8466	5.38	0.24	8878	45	---	---	4.82
"	144.3	2.18	14789	9662	6.56	0.13	24021	48	---	---	4.58
"	145.6	2.17	15326	9734	6.92	0.16	22947	48	---	---	4.08
"	145.1	0.56	---	---	---	---	---	---	2845	0	---
"	141.3	0.54	---	---	---	---	---	---	1832	40	---
"	143.4	0.55	---	---	---	---	---	---	1751	40	---
FRELTP-0m-3m-27-SNL/CSM	144.2	2.17	15126	9842	6.84	0.13	15468	90	---	---	3.87
"	144.6	2.18	14762	9775	6.62	0.11	20230	90	---	---	4.15
"	139.8	2.15	15521	8925	6.03	0.25	12845	90	---	---	3.34
"	144.8	0.54	---	---	---	---	---	---	2465	0	---
"	140.1	0.56	---	---	---	---	---	---	1406	0	---
"	145.3	0.52	---	---	---	---	---	---	3067	0	---
FRELTP-0m-3m-30-SNL/CSM	142.3	2.16	14711	9741	6.47	0.11	11106	53	---	---	5.55
"	157.0	2.22	14532	9625	6.97	0.11	8388	58	---	---	5.47
"	154.7	2.23	14614	8980	6.45	0.20	4324	63	---	---	5.10
"	142.6	0.53	---	---	---	---	---	---	2078	0	---
"	158.0	0.53	---	---	---	---	---	---	2142	25	---
"	159.9	0.56	---	---	---	---	---	---	1813	35	---
FRELTP-0m-3m-33-SNL/CSM	143.4	2.18	14894	9731	6.62	0.13	16085	90	---	---	4.33
"	140.7	2.16	14463	8713	5.61	0.22	9476	90	---	---	3.94
"	141.4	2.18	13698	8853	5.47	0.14	4524	90	---	---	5.61
"	146.0	0.51	---	---	---	---	---	---	2560	0	---
"	145.1	0.48	---	---	---	---	---	---	2477	0	---
"	145.7	0.53	---	---	---	---	---	---	1768	0	---

APPENDIX III

The individual results from the physical property tests performed at EMI are listed in the following table. Note that this is a summary table that does not show intermediate calculation steps.

SANDIA YMP PROJECT
PHYSICAL PROPERTY TEST RESULTS, cont'd
EARTH MECHANICS INSTITUTE

SAMPLE NUMBER (full)	DENSITY (lb/ft^3)	L/D RATIO	P-WAVE VELOCITY (ft/sec)	S-WAVE VELOCITY (ft/sec)	YOUNGS MOD (E6 psi)	POISSON RATIO	EQUIV L/D=2 STRENGTH (psi)	COMPRES LOAD ANGLE (deg)	TENSILE STRENGTH (psi)	TENSILE LOAD ANGLE (deg)	CAI
FRELTP-0m-3m-36-SNL/CSM	144.9	2.22	14750	9532	6.49	0.14	20650	58	---	---	4.35
"	144.3	2.18	15083	9918	6.86	0.12	21875	48	---	---	4.59
"	143.5	2.24	14588	8685	5.73	0.23	17977	60	---	---	4.31
"	142.6	0.53	---	---	---	---	---	---	2246	38	---
"	144.3	0.55	---	---	---	---	---	---	1988	0	---
"	144.7	0.54	---	---	---	---	---	---	1645	30	---
BB-0m-3m-44-SNL/CSM	144.3	1.92	14544	9932	6.54	0.06	8565	25	---	---	4.73
"	144.7	1.99	14594	10323	6.66	-0.00	6433	10	---	---	5.35
"	144.6	2.05	15088	9944	6.90	0.12	36122	10	---	---	3.62
"	143.4	0.47	---	---	---	---	---	---	2764	0	---
"	145.5	0.51	---	---	---	---	---	---	2627	65	---
"	143.5	0.50	---	---	---	---	---	---	2153	0	---
BB-0m-3m-46-SNL/CSM	144.6	2.12	14915	10055	6.84	0.08	23981	30	---	---	4.36
"	143.7	1.96	14711	9807	6.57	0.10	31062	30	---	---	3.47
"	142.3	2.07	14552	9810	6.41	0.08	17565	33	---	---	5.35
"	144.5	0.54	---	---	---	---	---	---	2668	55	---
"	143.5	0.50	---	---	---	---	---	---	1498	0	---
"	143.2	0.50	---	---	---	---	---	---	3204	0	---
GTB-32m-37m-47-SNL/CSM	141.2	2.08	13939	8712	5.46	0.18	14207	73	---	---	3.74
"	142.6	2.08	14646	9154	6.09	0.18	12056	63	---	---	4.65
"	144.2	2.05	14130	9065	5.89	0.15	15767	58	---	---	3.84
"	145.0	0.52	---	---	---	---	---	---	1590	0	---
"	146.3	0.53	---	---	---	---	---	---	2352	0	---
"	145.7	0.49	---	---	---	---	---	---	1894	20	---
GTB-32m-37m-48-SNL/CSM	144.1	2.18	13422	8555	5.28	0.16	19530	63	---	---	3.97
"	142.3	2.21	13700	8602	5.34	0.17	16244	65	---	---	4.57
"	143.9	2.20	13550	8791	5.46	0.14	14300	75	---	---	4.87
"	144.2	0.55	---	---	---	---	---	---	1598	0	---
"	144.4	0.51	---	---	---	---	---	---	1721	25	---
"	143.5	0.51	---	---	---	---	---	---	1825	90	---
GTB-32m-37m-49-SNL/CSM	142.3	2.11	13393	8399	5.10	0.18	19690	58	---	---	5.01
"	141.3	2.10	13538	8579	5.23	0.16	13637	65	---	---	4.11
"	141.7	2.11	13728	8472	5.24	0.19	13371	65	---	---	4.47
"	142.5	0.48	---	---	---	---	---	---	1275	25	---
"	141.8	0.50	---	---	---	---	---	---	1319	28	---
"	138.0	0.49	---	---	---	---	---	---	1371	0	---

Manufacturer	Rock Type	Specific Gravity	Quartz %	Compres Strength (MPa)	Tensile Strength (MPa)	Young's Modulus (MPa)	Secant Modulus (MPa)	Cerchar Abrasivity
Anderson Strathclyde PLC 47 Broad Street Glasgow G40 2QW Scotland	Banded Rhyolite Tuff w/ glass	not measured	> 25%	144 MPa (20,885 psi)	8.6 MPa (1,247 psi)	not measured	not measured	3.1
Atlas Copco / Eichoff Hunscheidtstrasse 154 4630 Bochum 1 W. Germany	Quartz Porphyry	not measured	> 25%	72.4 MPa (10,500 psi)	8.4 MPa (1,220 psi)	not measured	not measured	4.2
Dosco Overseas Eng. Ollerton Road Tuxford Nr Newark Notts NG22 0PQ England	Tuff	not measured	> 40%	148 MPa (21,460 psi)	8.6 MPa (1,247 psi)	not measured	not measured	3.9 - 4.2
Eimco International Earlsway, Team Valley Gateshead, NE11 0SB England	No Response	No Response	No Response	No Response	No Response	No Response	No Response	No Response
Paurat GmbH P.O. Box 02 12 20 D-4223 Voerde W. Germany	Quartz Porphyry	not measured	72%	175.9 MPa (25,668 psi)	12.7 MPa (1,816 psi)	not measured	not measured	wear coefficient 1.737 N/mm
Voest Alpine GmbH P.O. Box 1 Zeltweg A-8740 Austria	Rhyolite Tuff	not measured	> 65%	75.4 MPa (10,780 psi)	8.35 MPa (1,194 psi)	9155 MPa (1.309E6 psi)	9195 MPa (1.314E6 psi)	index of cuttability 140 MPa
Westfalia Lunen D-4670 Lunen W. Germany	Quartz Porphyry	not measured	> 25% (0.185mm diam)	224 MPa (32,050 psi)	8.9 MPa (1,290 psi)	not measured	not measured	wear coefficient 0.412 N/mm
J.E. Friant & Assoc. 1352 S.W. 175th St. Seattle, WA 98166 (see note)	Welded Tuff	2.31	30%	157 MPa (22,745 psi)	not measured	not measured	not measured	not measured

Note: Figures 10 through 25 of this report were provided by J.E. Friant & Associates. They also performed point load tests and punch tests (with spherical and cutter section indenters).

APPENDIX IV

This is Figure 25 from Broch and Franklin (1972). See the original paper for a complete description of the data reduction process.

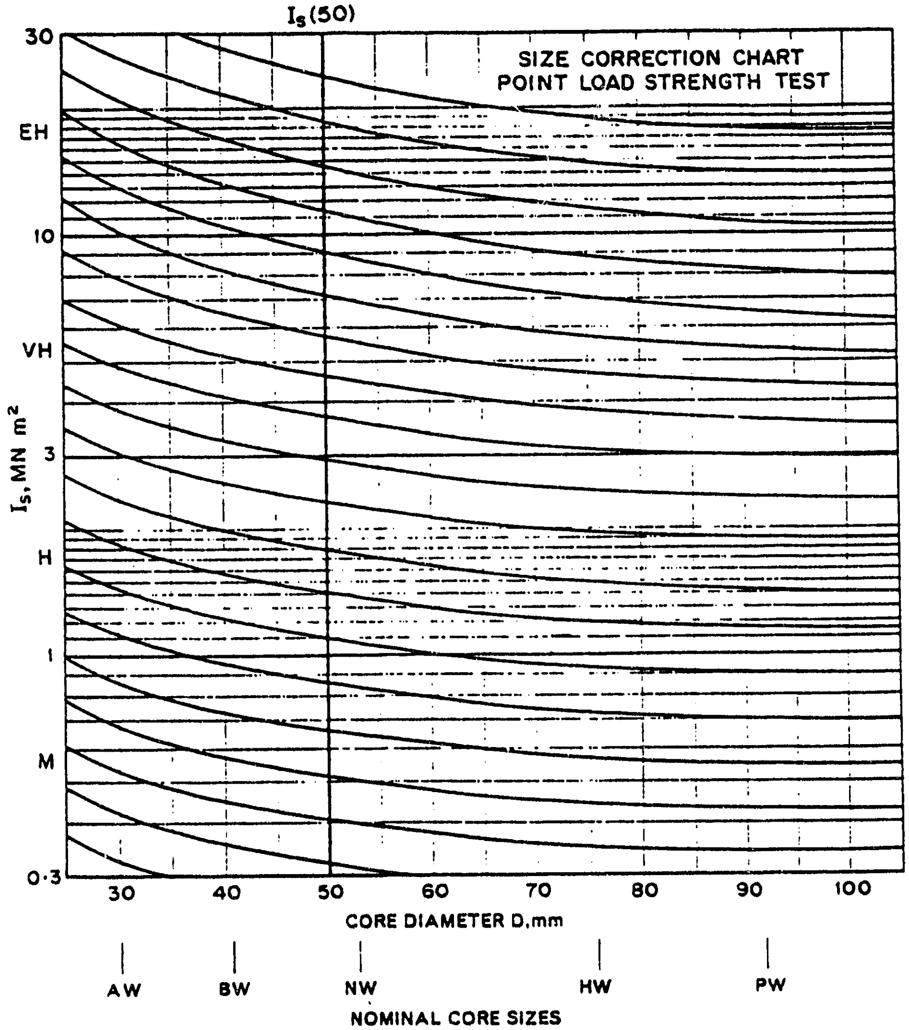


FIG. 25. Size correction chart for point-load strength testing (from Fig. 9).

APPENDIX V

The following graphs illustrate the linear regression performed as part of the determination of the effects of the visible fabric anisotropy on uniaxial compressive strength, splitting tensile strength, and ultrasonic pulse velocity.

The adequacy of the regression models then was evaluated by testing the null hypothesis (H_0) that the population correlation coefficient (R) was equal to zero, using the t statistic:

$$t_0 = \text{sqr root } [\frac{r * (n - 2)}{1 - r^2}]$$

where: r = sample correlation coefficient
n = number of tests

The null hypothesis was rejected if t_0 was greater than $t_{a/2,n-2}$, where a = 5% ($t_{a/2,n-2}$ values obtained from Hines and Montgomery, 1980, Table IV). The level of confidence was 95% (100% - a).

The tables on the following page list the pertinent parameters used to test the null hypothesis on uniaxial compressive strengths, splitting tensile strengths, and P-wave velocities. The null hypothesis could not be rejected at the 95% level of confidence for any of the sample groups in any of the three data sets. Following the tables are plots of the linear regression models used.

Table IV-1

Statistical determination of the effect of fabric anisotropy on uniaxial compressive strength. H_0: R = 0.

tuff origin	r	n	t_0	$t_{0.025,n-2}$	reject H_0?
Fran Ridge	0.395	21	1.876	2.086	NO
Busted Butte	0.043	6	0.086	2.571	NO
G-Tunnel	0.448	9	1.324	2.306	NO

Table IV-2

Statistical determination of the effect of fabric anisotropy on splitting tensile strength. H_0: R = 0.

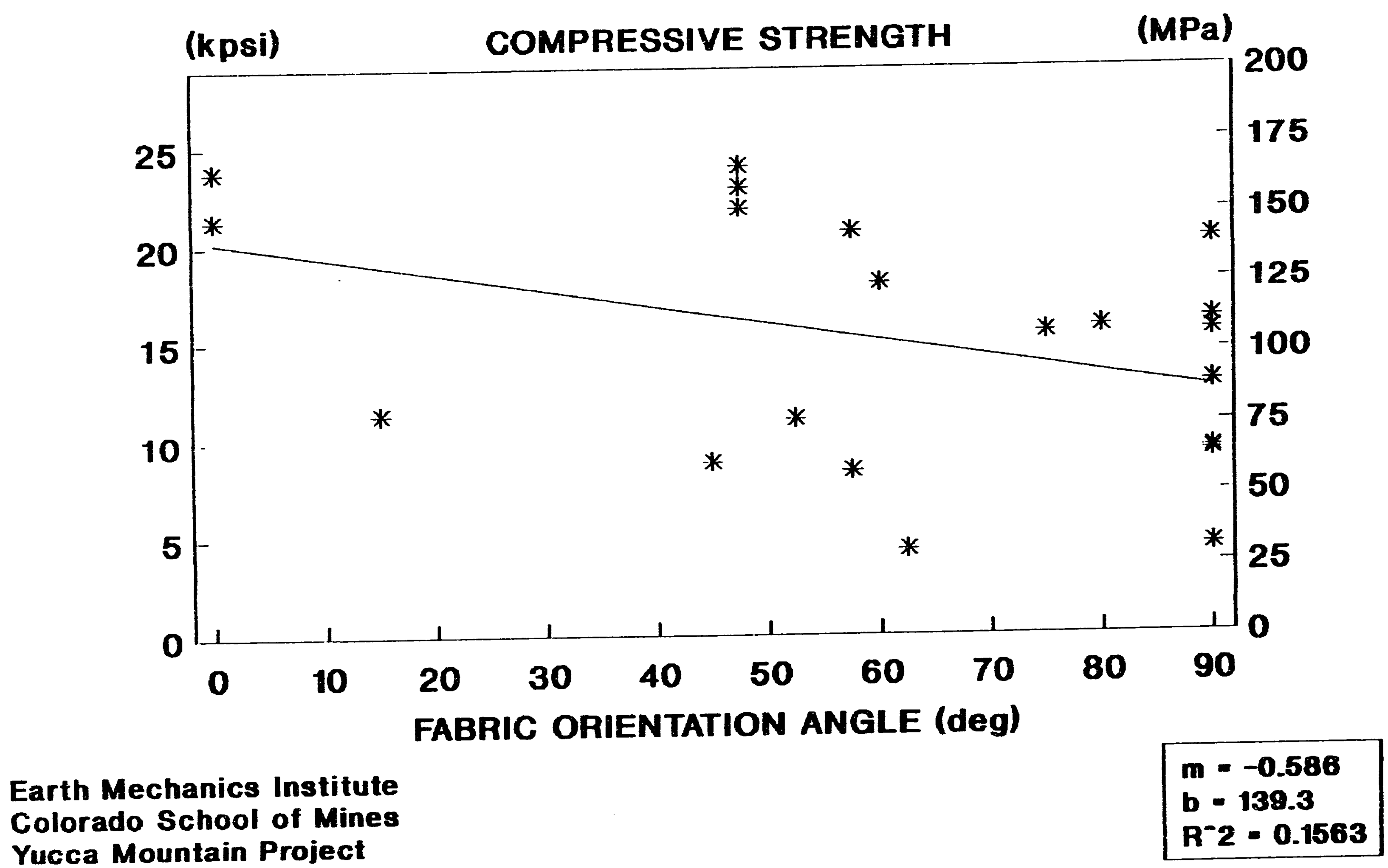
tuff origin	r	n	t_0	$t_{0.025,n-2}$	reject H_0?
Fran Ridge	0.278	22	1.296	2.080	NO
Busted Butte	0.210	6	0.429	2.571	NO
G-Tunnel	0.025	9	0.066	2.306	NO

Table IV-3

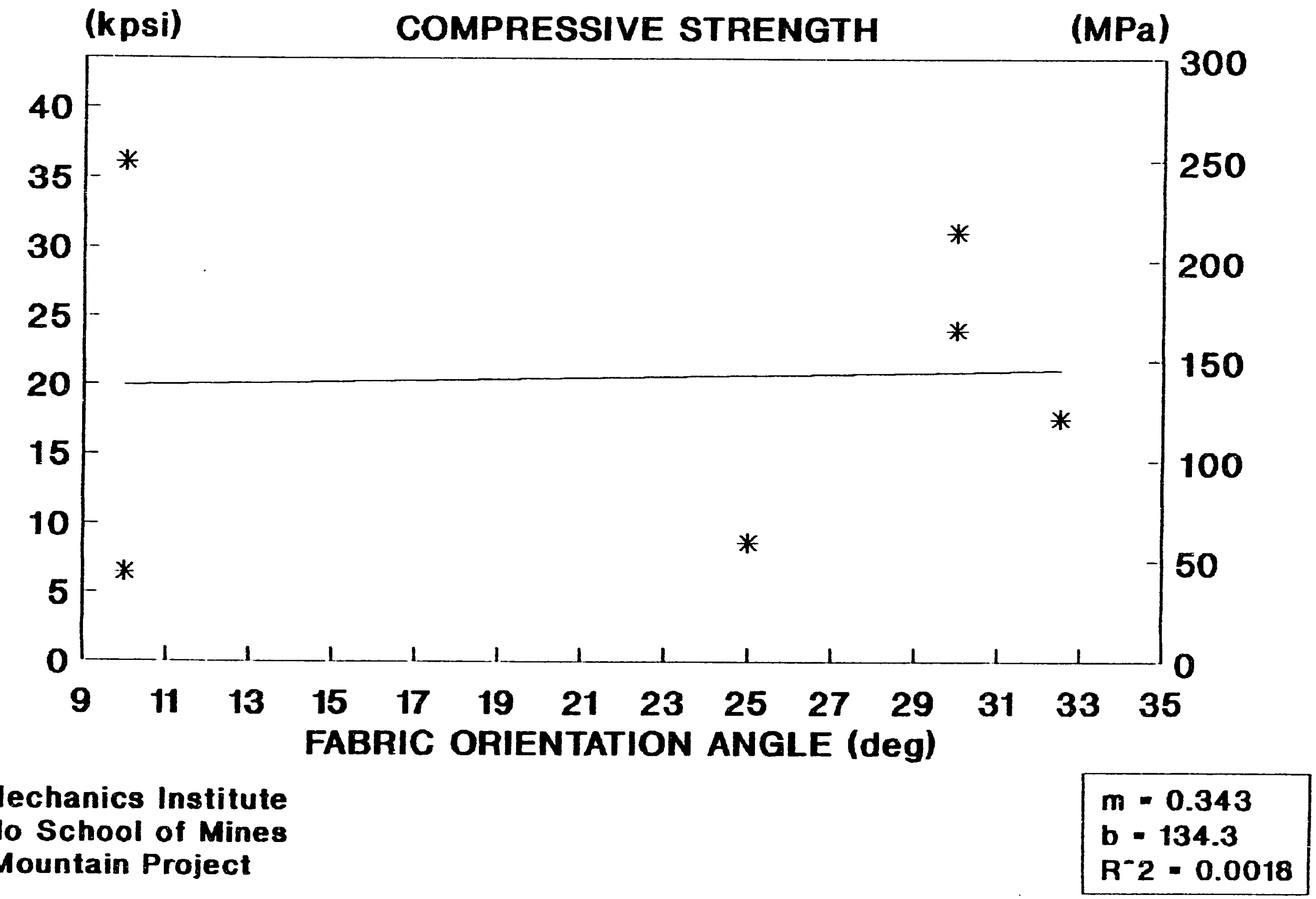
Statistical determination of the effect of fabric anisotropy on P-wave velocity. H_0: R = 0.

tuff origin	r	n	t_0	$t_{0.025,n-2}$	reject H_0?
Fran Ridge	0.333	21	1.539	2.086	NO
Busted Butte	0.331	6	0.701	2.571	NO
G-Tunnel	0.110	9	0.292	2.306	NO

ANISOTROPY ANALYSIS
LINEAR REGRESSION
FRAN RIDGE SAMPLES

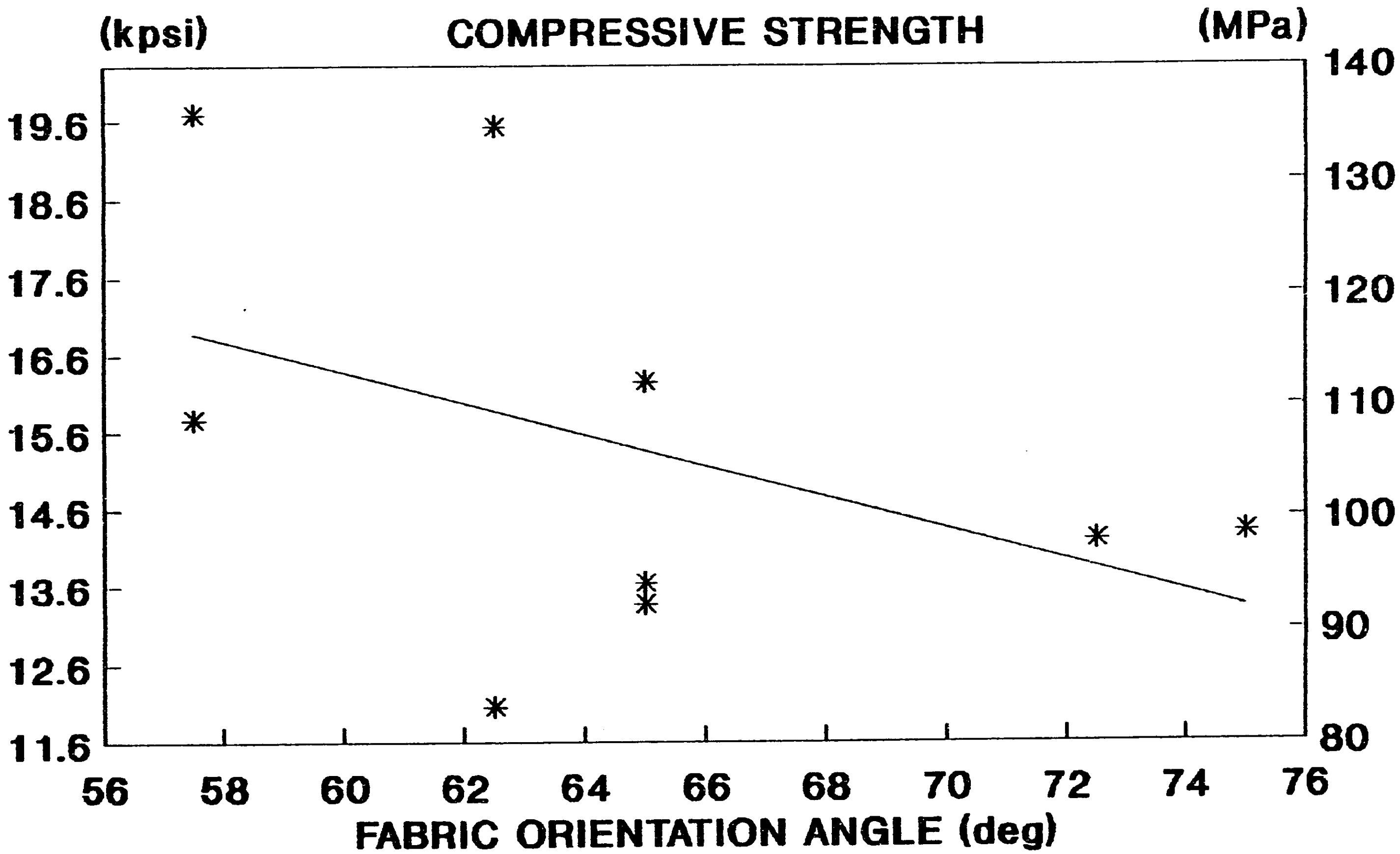


ANISOTROPY ANALYSIS
LINEAR REGRESSION
BUSTED BUTTE SAMPLES



Earth Mechanics Institute
Colorado School of Mines
Yucca Mountain Project

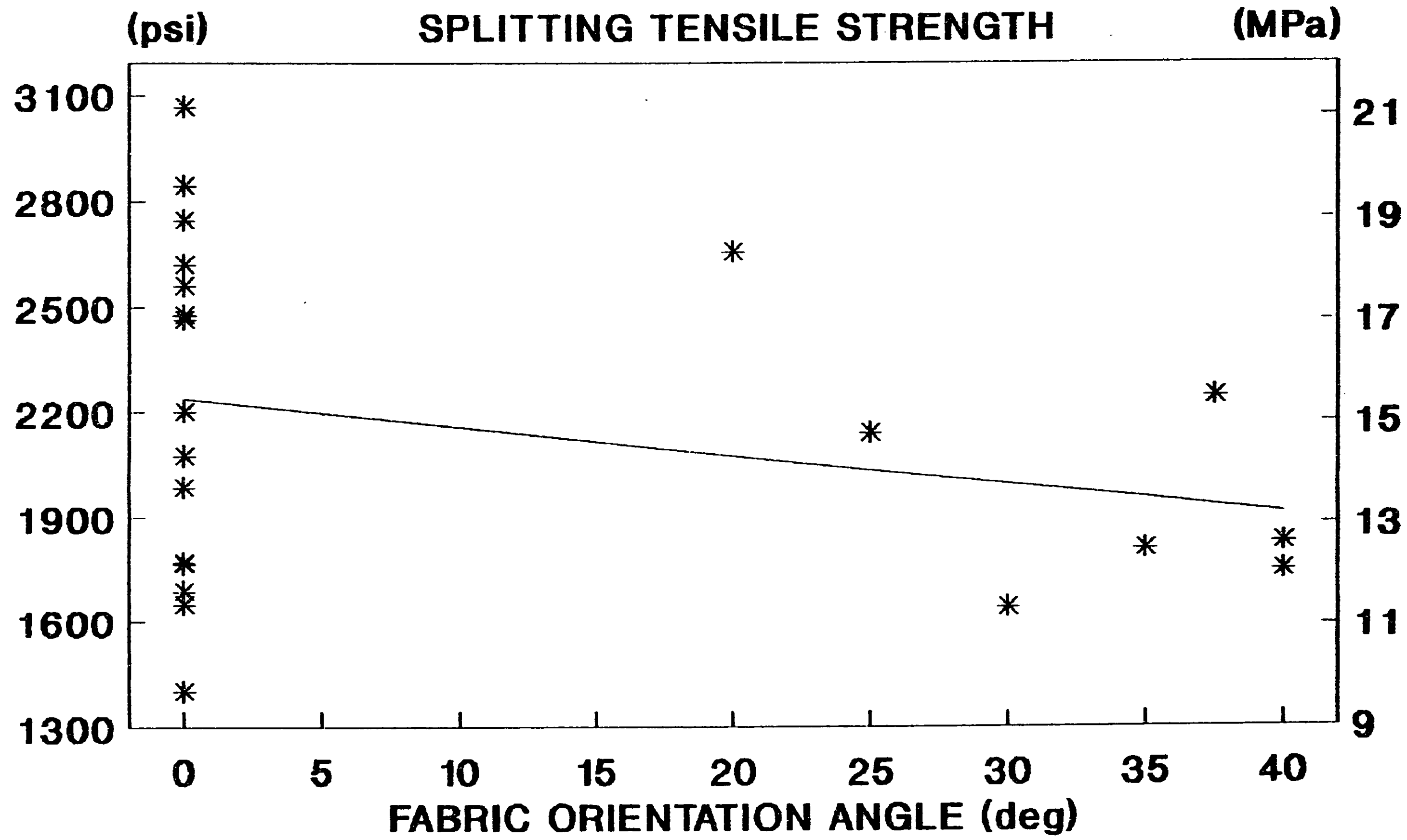
ANISOTROPY ANALYSIS
LINEAR REGRESSION
G-TUNNEL SAMPLES



Earth Mechanics Institute
Colorado School of Mines
Yucca Mountain Project

m = -1.395
b = 196.6
R^2 = 0.2003

ANISOTROPY ANALYSIS
LINEAR REGRESSION
FRAN RIDGE SAMPLES



m = -0.0554
b = 15.44
R^2 = 0.0775

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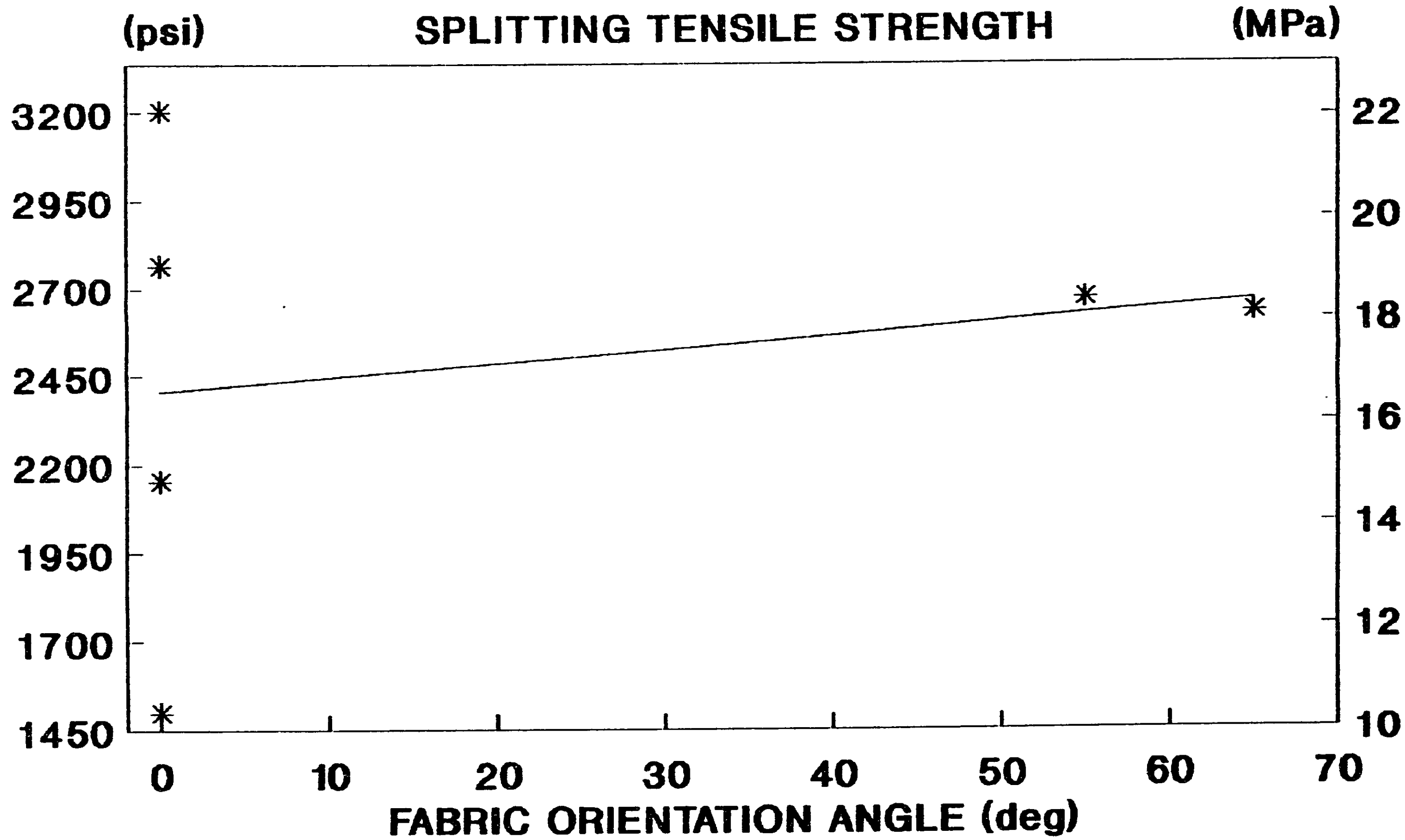
ANISOTROPY ANALYSIS
LINEAR REGRESSION
BUSTED BUTTE SAMPLES



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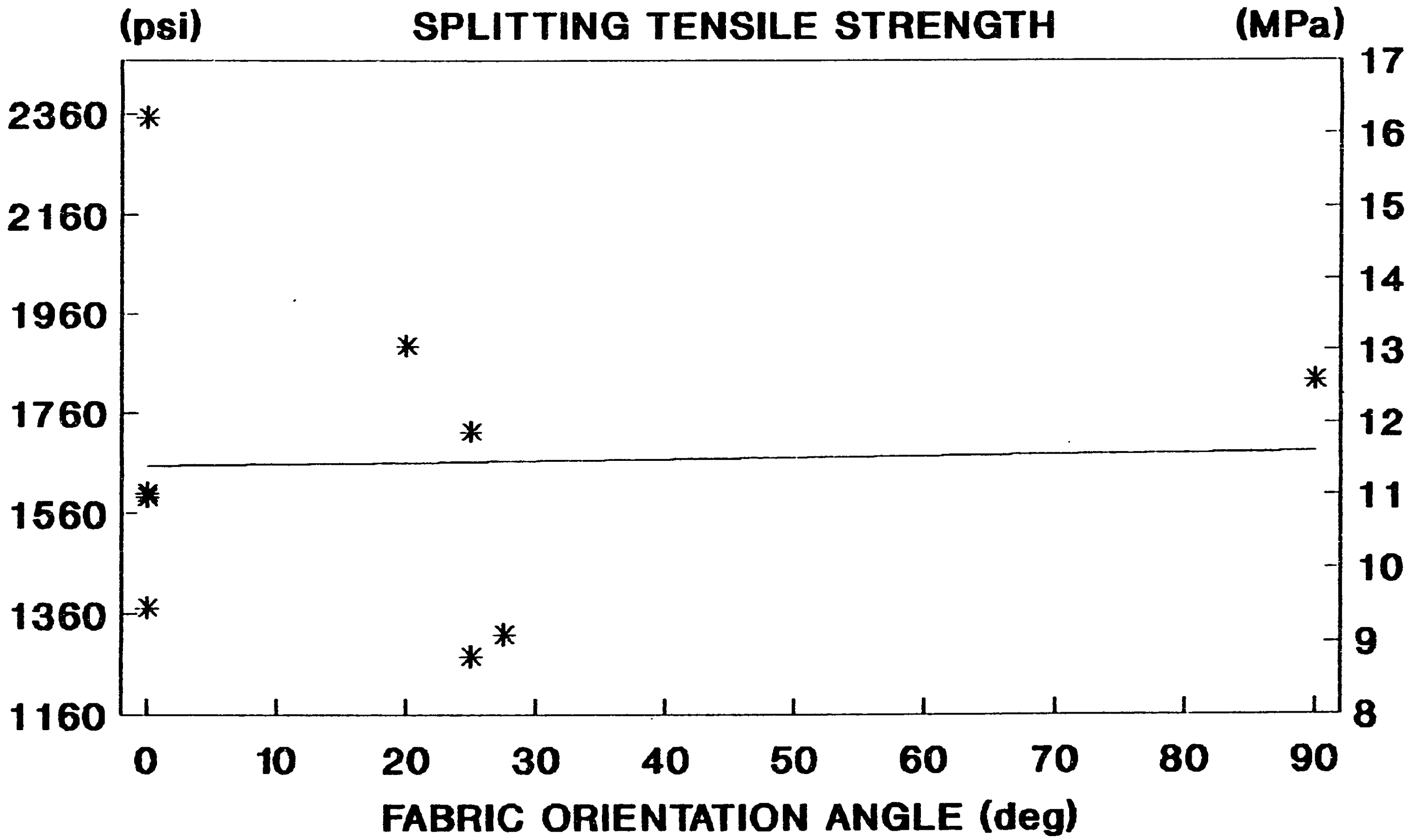
m = 0.0273
b = 16.59
R^2 = 0.0440

ANISOTROPY ANALYSIS
LINEAR REGRESSION
G-TUNNEL SAMPLES



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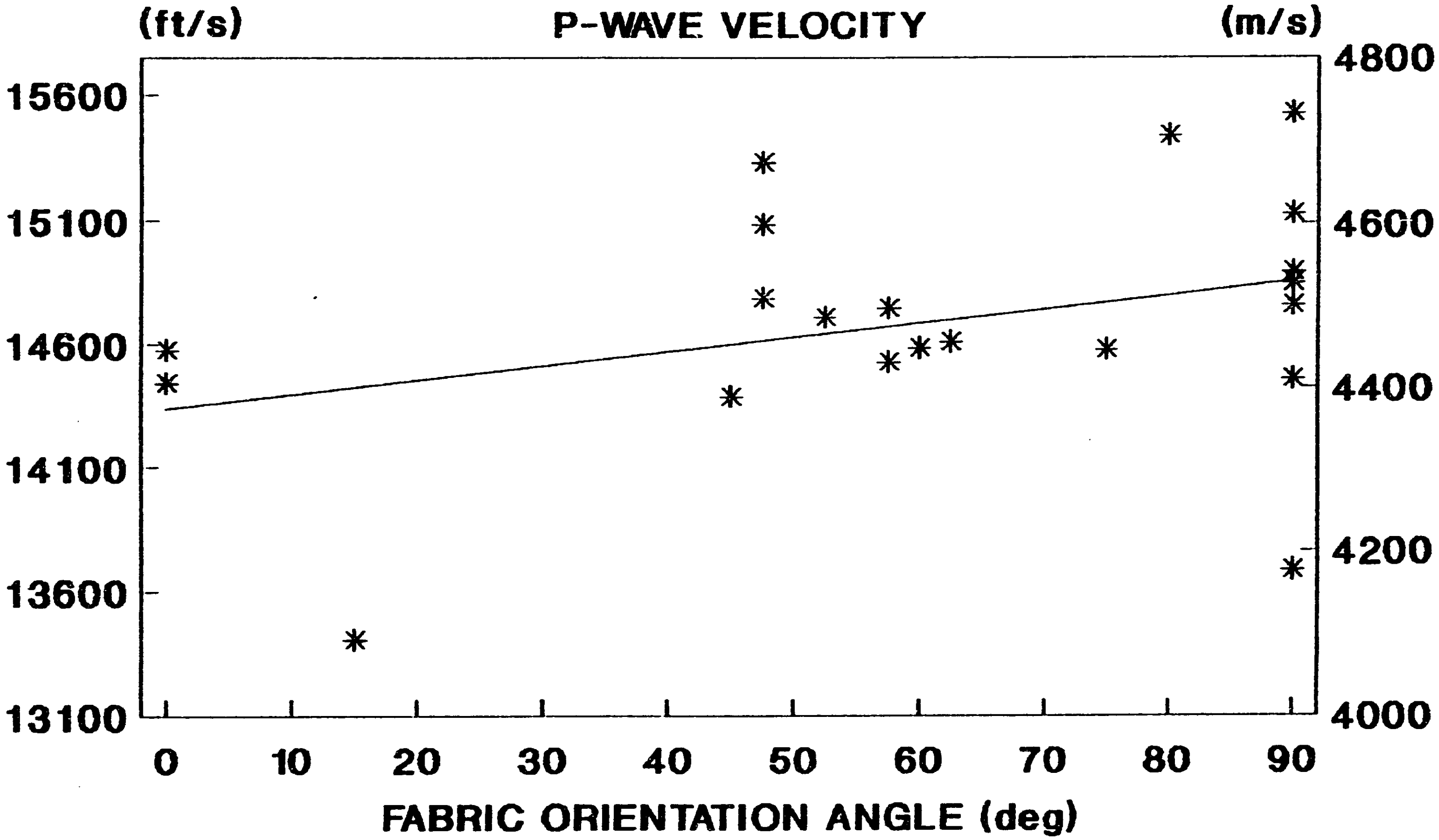
m = 0.002
b = 11.41
R^2 = 0.0006

ANISOTROPY ANALYSIS
LINEAR REGRESSION
FRAN RIDGE SAMPLES



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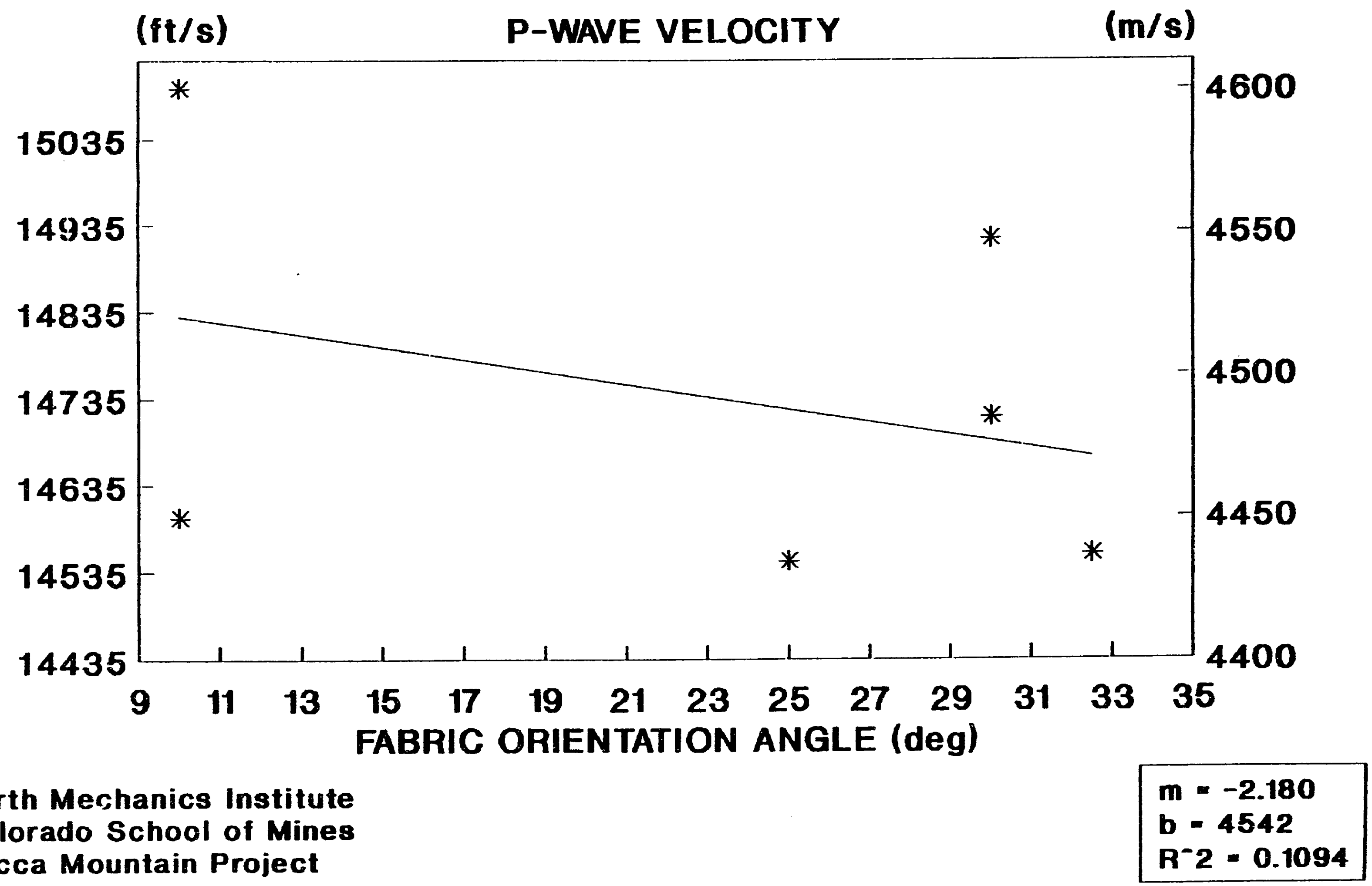
m = 1.735
b = 4374
R^2 = 0.1108

ANISOTROPY ANALYSIS
LINEAR REGRESSION
BUSTED BUTTE SAMPLES



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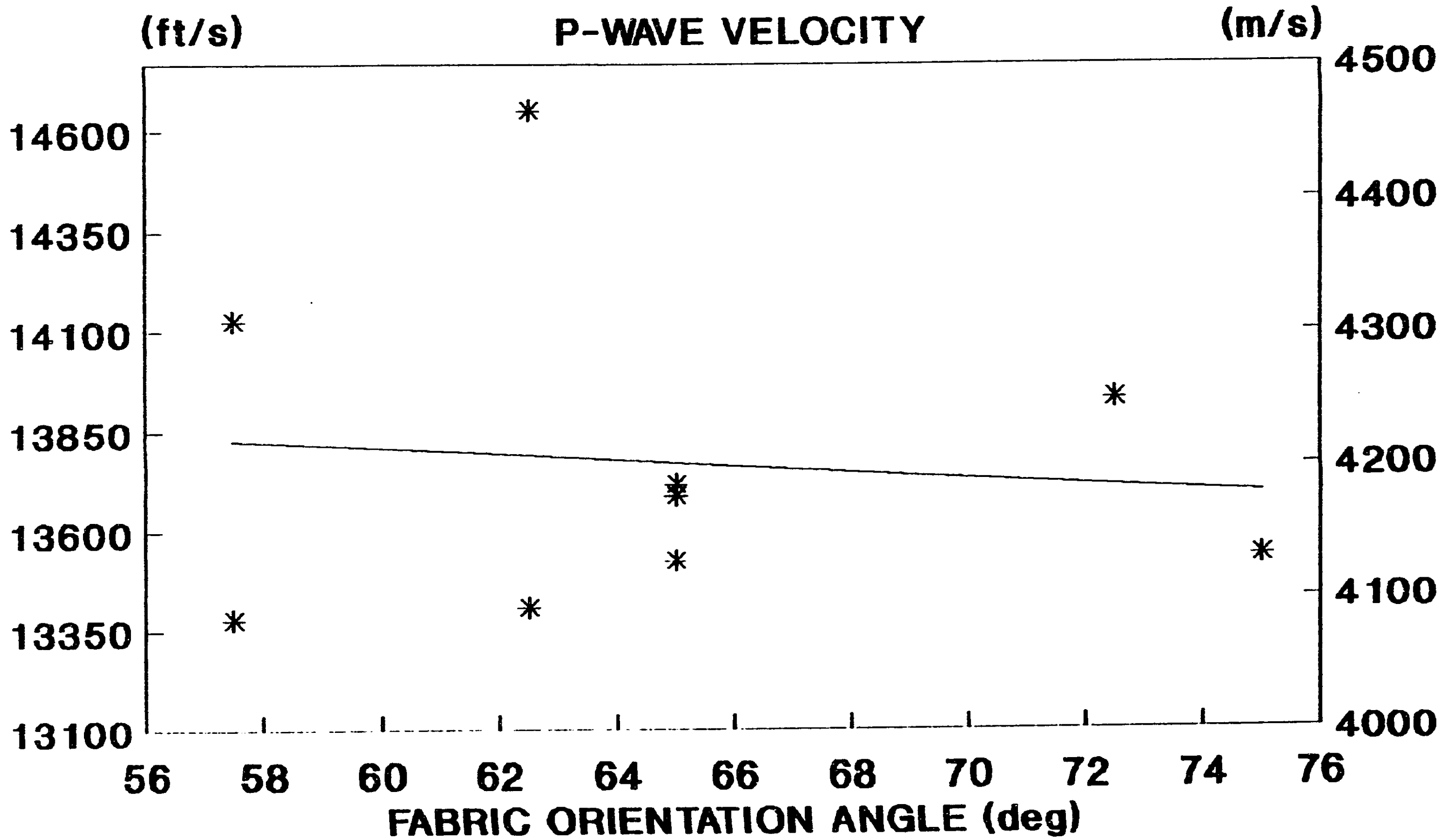
ANISOTROPY ANALYSIS
LINEAR REGRESSION
G-TUNNEL SAMPLES



m = -2.30
b = 4349
R^2 = 0.0120

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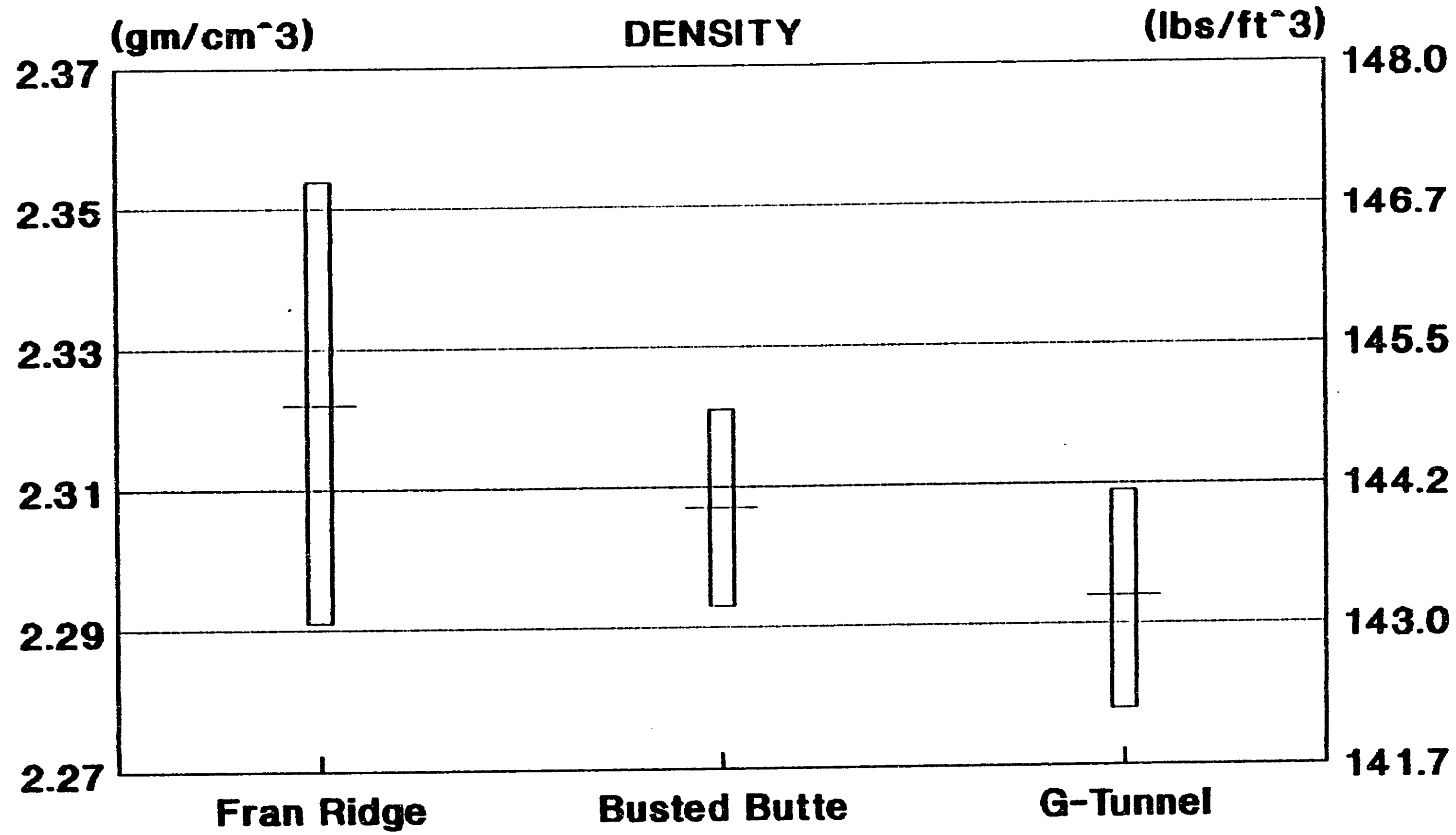
APPENDIX VI

The following plots illustrate average physical property values along with their 95% confidence limits. These plots are a different way of viewing the information presented in tables in the body of this report.

MEASURED BULK DENSITY
AVERAGES AND 95% CONFIDENCE INTERVALS
GROUPED ACCORDING TO SAMPLE ORIGIN



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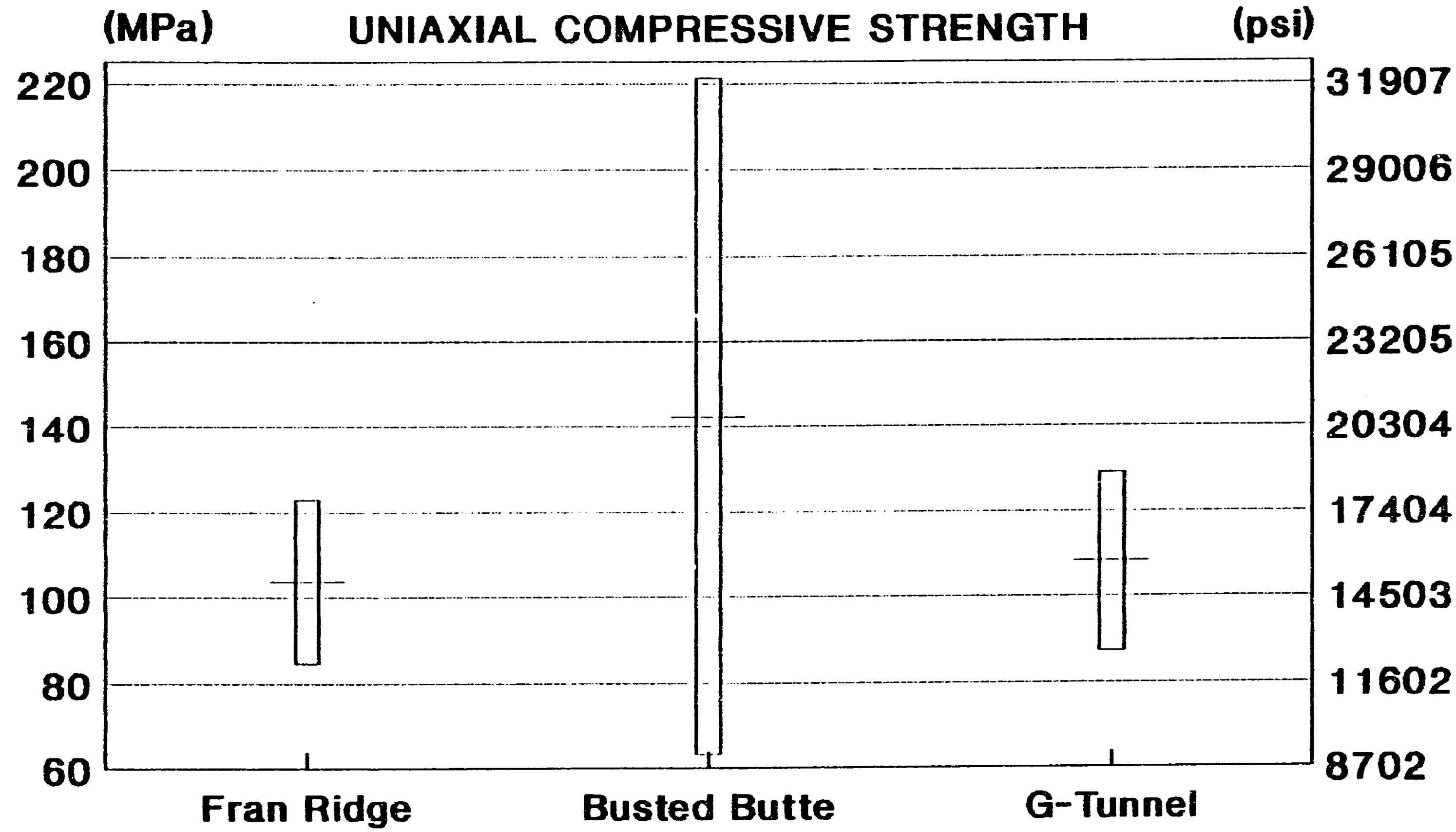
L/D = 2 UNIAXIAL COMPRESSIVE STRENGTH AVERAGES AND 95% CONFIDENCE INTERVALS GROUPED ACCORDING TO SAMPLE ORIGIN



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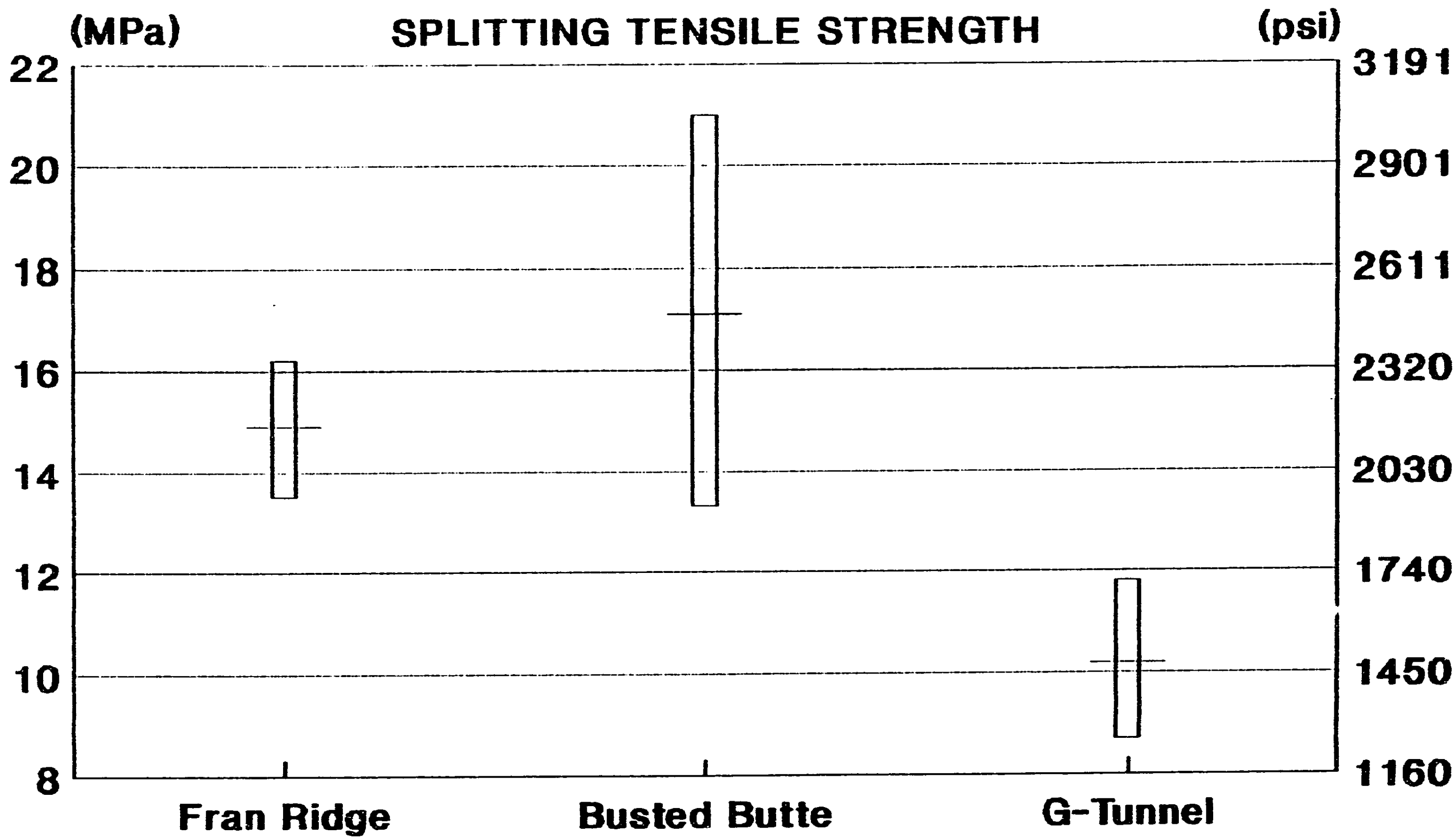
MEASURED SPLITTING TENSILE STRENGTH AVERAGES AND 95% CONFIDENCE INTERVALS GROUPED ACCORDING TO SAMPLE ORIGIN



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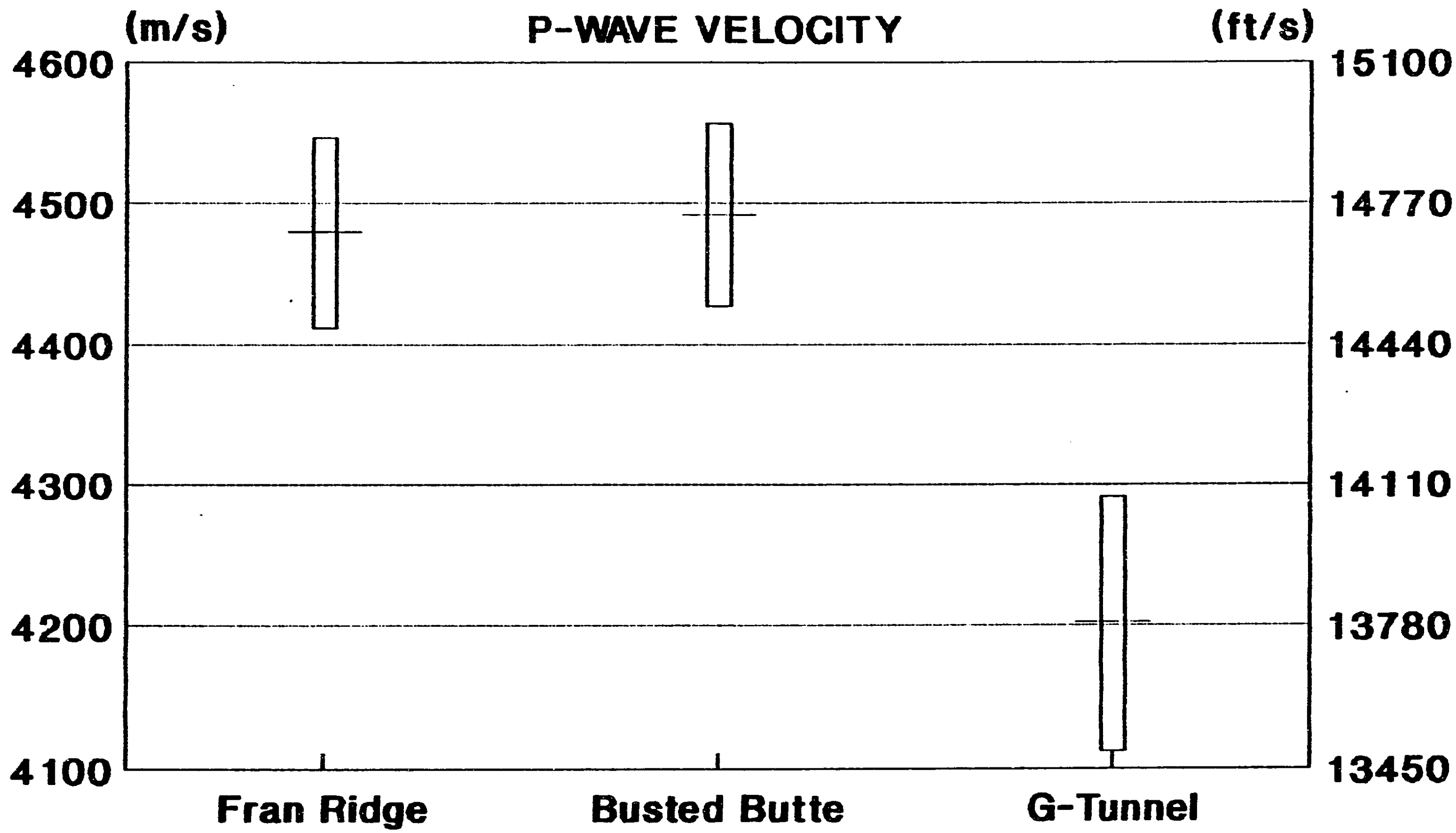
MEASURED P-WAVE VELOCITY
AVERAGES AND 95% CONFIDENCE INTERVALS
GROUPED ACCORDING TO SAMPLE ORIGIN



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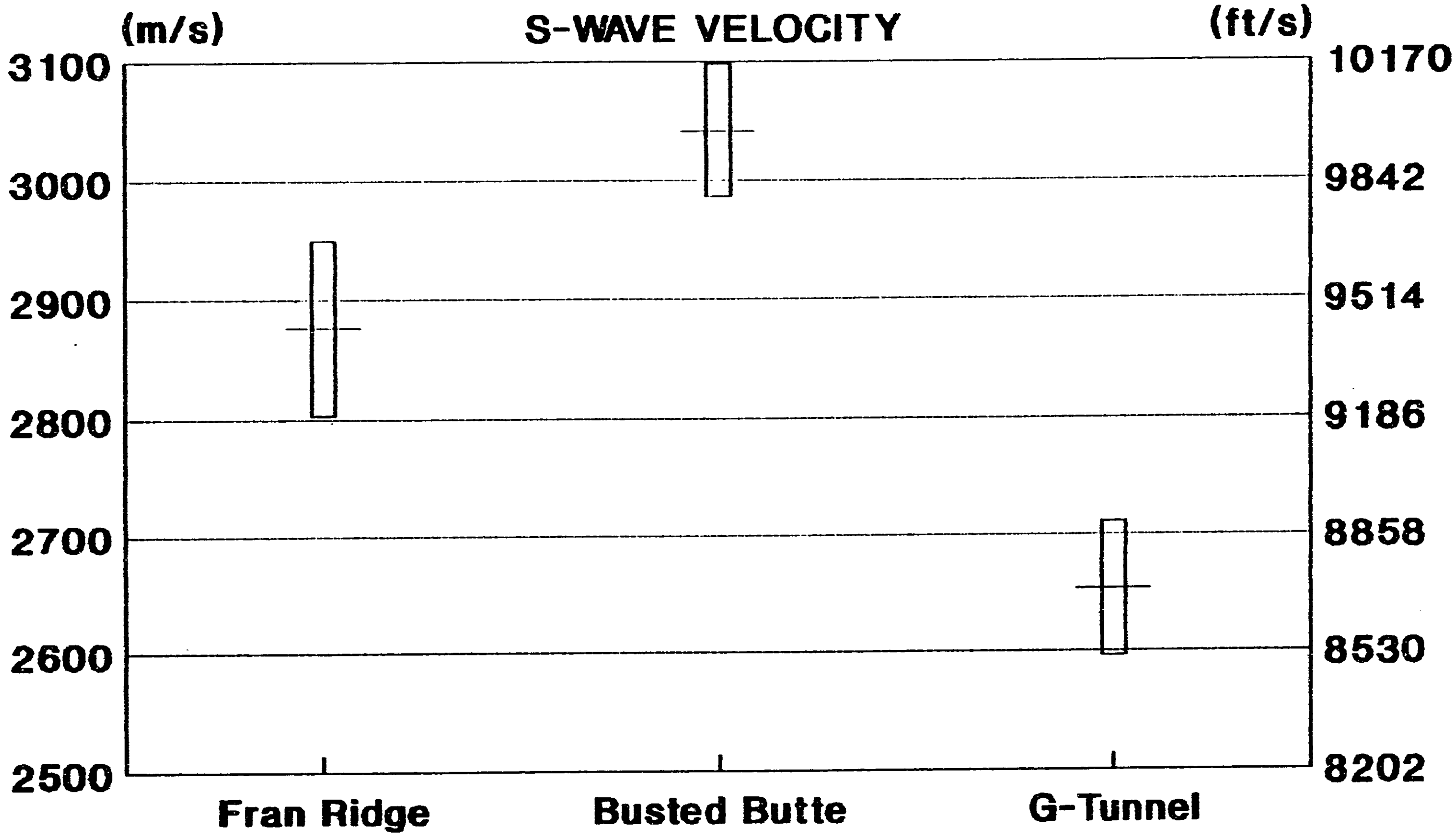
MEASURED S-WAVE VELOCITY
AVERAGES AND 95% CONFIDENCE INTERVALS
GROUPED ACCORDING TO SAMPLE ORIGIN



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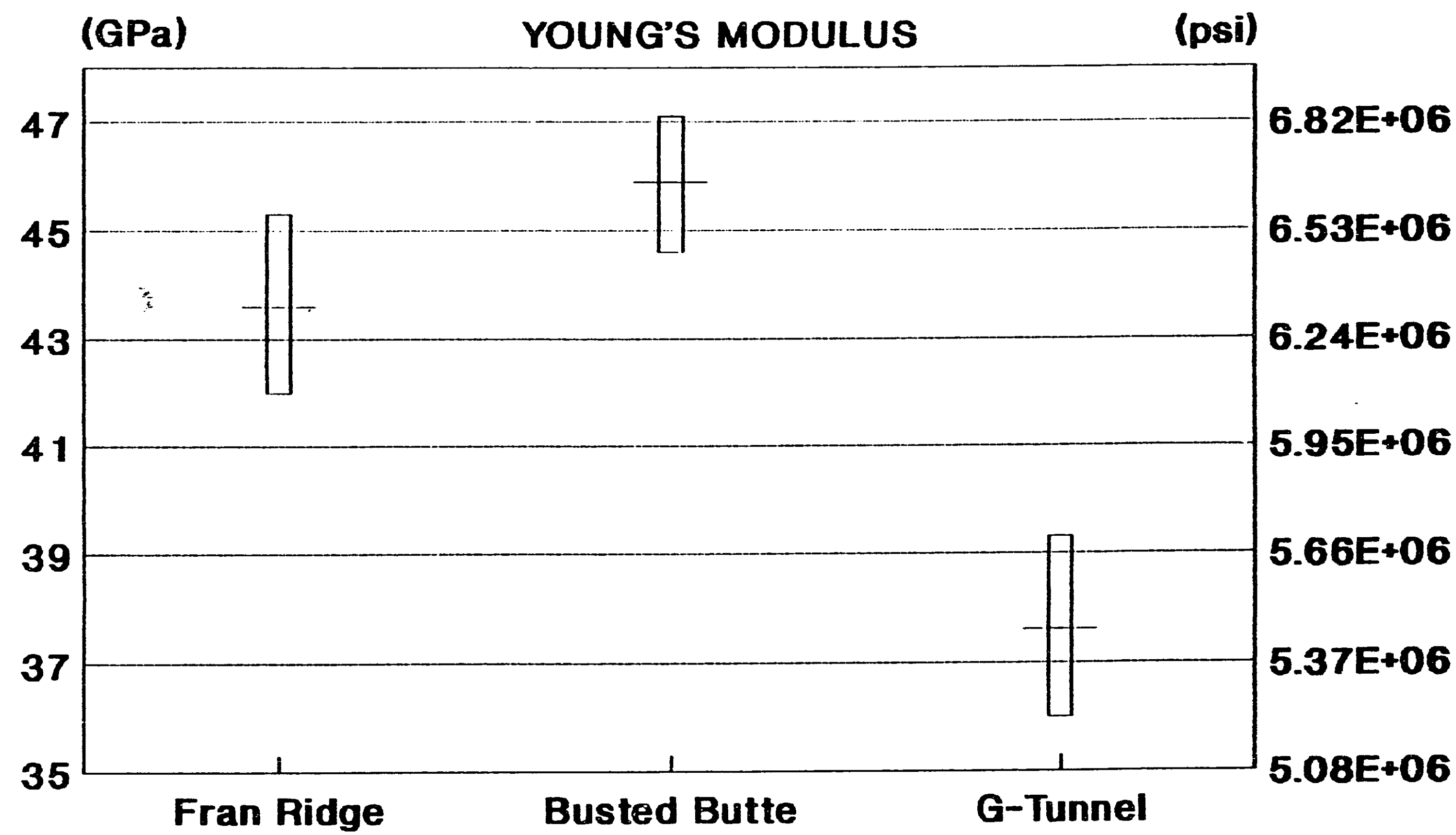
MEASURED YOUNG'S MODULUS
AVERAGES AND 95% CONFIDENCE INTERVALS
GROUPED ACCORDING TO SAMPLE ORIGIN



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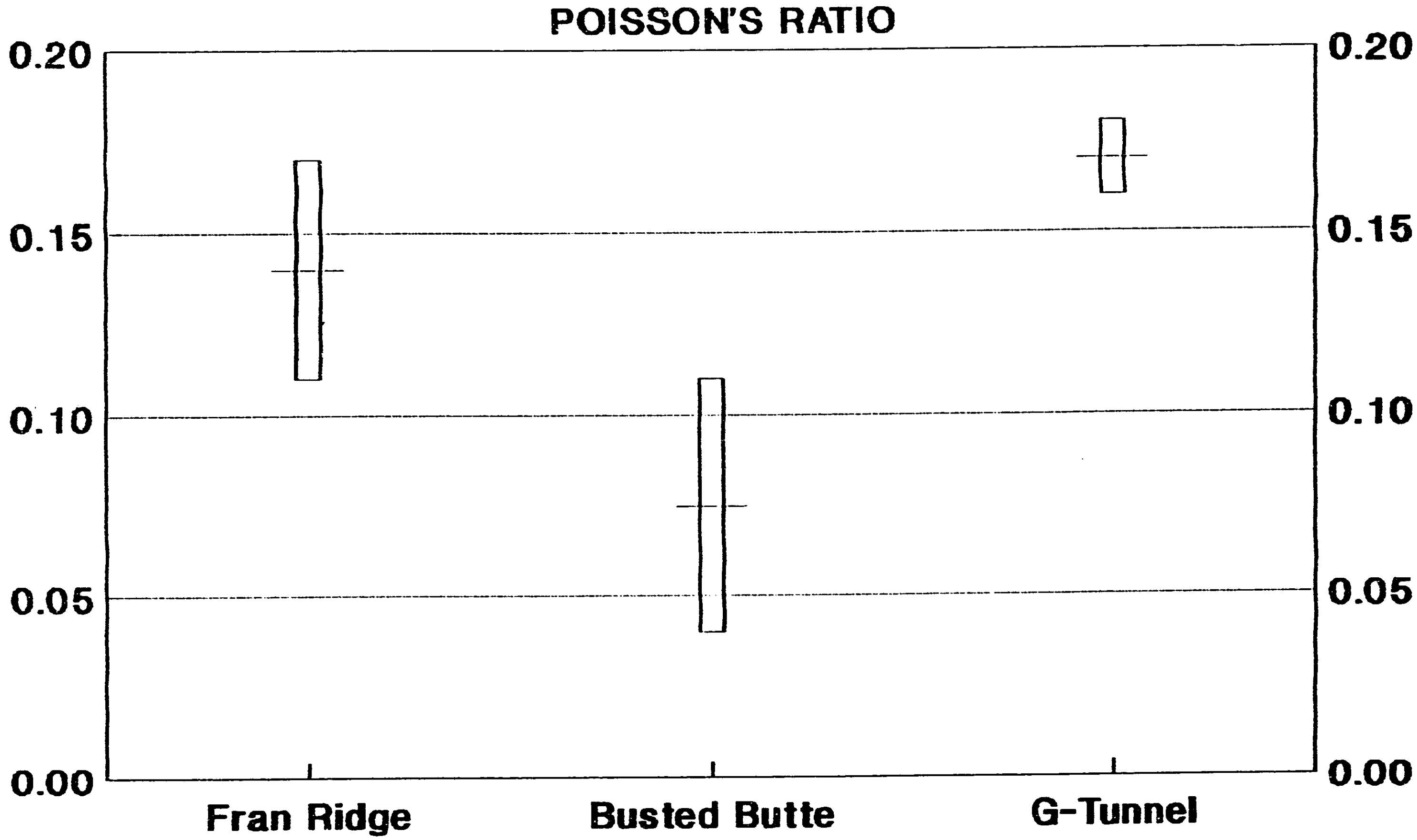
MEASURED POISSON'S RATIO
AVERAGES AND 95% CONFIDENCE INTERVALS
GROUPED ACCORDING TO SAMPLE ORIGIN



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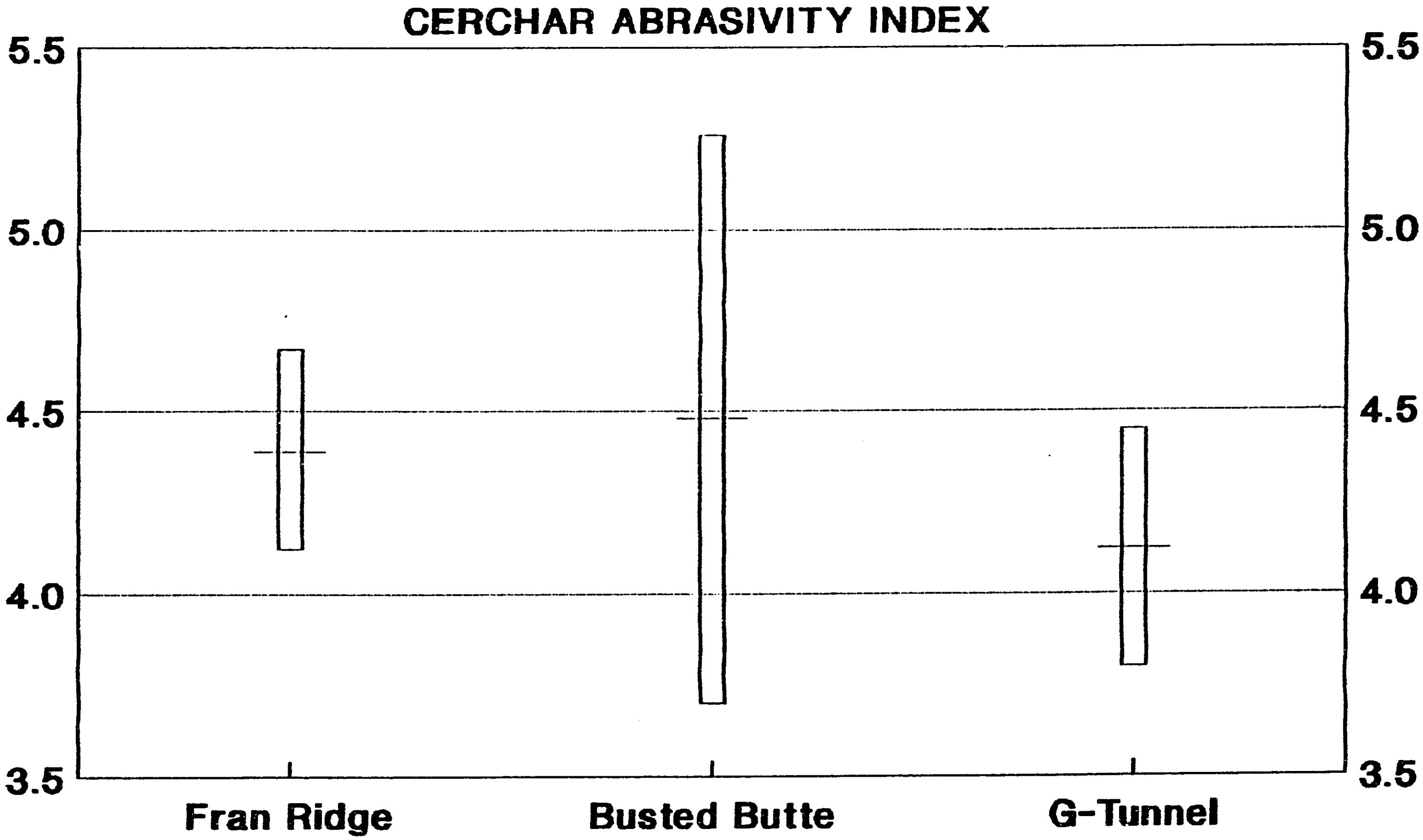
MEASURED CERCHAR ABRASIVITY AVERAGES AND 95% CONFIDENCE INTERVALS GROUPED ACCORDING TO SAMPLE ORIGIN



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APPENDIX VII

The following conversion factors were used throughout this report:

1 millimeter (mm)	-	0.0394 in.
1 centimeter (cm)	-	0.394 in.
1 meter (m)	-	3.28 ft or 39.4 in.
1 megapascal (MPa)	-	145.03 psi
1 gigapascal (GPa)	-	145030 psi
1 gram (g)	-	0.00220 lbm
1 kilogram (kg)	-	2.20 lbm
1 kilonewton (kN)	-	225 lbf
1 meganewton (MN)	-	225000 lbf

APPENDIX VIII

The following table summarizes the findings of the thin-section petrographic analysis; the final report follows.

NUMBER (short)	WEATHERING	COMPACTION	DEGREE WELDING	% CRYSTAL FRAGS	% PUMICE LAPILLI	% LITHIC FRAGS	% SHARDS & ASH	ROCK TYPE
YMP3C(H)	none	mod-strong	mod-strong	3	5-7	5	80-85	Fran Ridge
YMP3C(H)	none	mod	mod-strong	1-2	25-30	1-2	60-65	Fran Ridge
YMP3C(H)		mod		3	10-12	3-4	85-90	Fran Ridge
YMP4(H)	none	strong		3	5-7	5-7	80-84	Fran Ridge
YMP4(H)	none	mod-strong	strong	1-2	3-4	5-7	85-90	Fran Ridge
YMP4(H)	none	well-devel		1-2	0	3-4	95	Fran Ridge
YMP36B(H)		well-devel		3-5	2-3	3-5	85-90	Fran Ridge
YMP36B(H)	none	well-devel		3	2	2	90-95	Fran Ridge
YMP36B(H)	none	well-devel	well-devel	3	10	10-15	70-75	Fran Ridge
YMP46(H)	none	well-devel	densely,firm	3-5	0	15	75-80	Busted Butte
YMP46(H)		strong	firmly	3	0	10-15	85-90	Busted Butte
YMP46(H)	none	well-devel		3	6-7	7-8	80-85	Busted Butte
YMP49(1A)		well-devel	strong	15	10-15	0	65-70	G-Tunnel
YMP49(1B)	none			15-18	25-30	0	45-50	G-Tunnel
YMP49(2A)		well-devel		5-7	15-20	7-10	55-60	G-Tunnel
YMP49(2B)	none	well-devel	tightly	7	20	10-15	55-60	G-Tunnel
YMP49(3A)	none	well-devel		7-12	25-30	5	50-55	G-Tunnel
YMP49(3B)	none	well-devel		5-7	30-35	5-7	40-45	G-Tunnel

NUMBER (short)	IRON-BEARING QUARTZ SPHERULITIC REPLACEMENT	CALCITIC REPLACEMENT	SANIDINE	PLAG	PUMICE LAPILLI	LITHICS	VITRIC SHARDS	HEMATITE FLAKES	LITHO-PHYSAE	ROCK TYPE
YMP3C(N)	pervasive		x	x		x	x	x	x	Fran Ridge
YMP3C(H)	nearly all shards & lapilli to dif degrees		x	x	x	x	x	x	x	Fran Ridge
YMP3C(H)			x	x	x	x	x	x		Fran Ridge
YMP4(N)	80% of shards		x	x		x	x	x		Fran Ridge
YMP4(H)	90-95% of shards		x	x		x	x			Fran Ridge
YMP4(H)	100% of shards		x	x		x		x		Fran Ridge
YMP36B(N)		patchy	x	x			x	x		Fran Ridge
YMP36B(H)		patchy 7-8%	x	x	x					Fran Ridge
YMP36B(H)	starts from veinlets	patchy areas, starts fr. veinlets	x	x		x	x			Fran Ridge
YMP46(N)	90% of shards		x	x		x	x			Busted Butte
YMP46(H)	all shards		x	x		x	x			Busted Butte
YMP46(H)	95% of shards		x	x	x	x	x			Busted Butte
YMP49(1A)			x	x	x	x		x		G-Tunnel
YMP49(1B)			x		x	x	x	x		G-Tunnel
YMP49(2A)			x		x	x	x	x		G-Tunnel
YMP49(2B)			x		x	x	x	x		G-Tunnel
YMP49(3A)	outside lapilli		x		x	x	x	x		G-Tunnel
YMP49(3B)	spotty		x		x	x		x		G-Tunnel

NUMBER (short)	SILICA SPHERULS	BIOTITE	HEMATITE CRYSTALS	FRAC FILLING	FRAC WIDTH (mm)	FRAC LENGTH (mm)	% POROSITY	% PERM	ROCK TYPE
YMP3C(N)	X		X	quartz	0.010	1.5	< 2-3	< 2-3	Fran Ridge
				hematite	0.010	1.0			
				hematite	0.010	1.3			
				hematite	0.010	0.3			
				hematite	0.010	0.5			
YMP3C(H)	X	X	X	hematite	0.010	6.8			Fran Ridge
				hematite	0.010	0.5			
				hematite	0.005	0.9			
				hematite	0.010	0.8			
YMP3C(H)	X		X	quartz	0.010	6.8	1-2	1-2	Fran Ridge
				quartz	0.010	13.0			
YMP4(N)	X	X	X		0.005	0.4	2-3	2-3	Fran Ridge
					0.010	5.5			
YMP4(H)	X	X	X						Fran Ridge
YMP4(H)	X		X				2-3	2-3	Fran Ridge
YMP36B(N)			X	calcite	0.240	> 10			Fran Ridge
				quartz	1.000	> 10			
YMP36B(H)	X		X	quartz	0.230	7.0	2-3	2-3	Fran Ridge
				quartz	0.010	9.0			
YMP36B(H)	X		X	quartz	0.010	7.0	2-3	2-3	Fran Ridge
				quartz	0.010	7.0			
				calcite	0.900	8.0			
YMP46(N)	X	X	X				1-2	1-2	Busted Butte
YMP46(H)			X	hematite		1.0	2-3	2-3	Busted Butte
						3.0			
YMP46(H)	X		X	hematite	0.010	0.8	2-3	2-3	Busted Butte
YMP49(1A)			X				3-5	< 1	G-Tunnel
YMP49(1B)							4-5	< 1	G-Tunnel
YMP49(2A)	X						5-8	< 1	G-Tunnel
YMP49(2B)							5-8	< 1	G-Tunnel
YMP49(3A)	X		X				7-10	< 2	G-Tunnel
YMP49(3B)	X								G-Tunnel

APPENDIX C

The following conversion factors were used throughout this report:

1 millimeter (mm)	=	0.0394 in.
1 centimeter (cm)	=	0.394 in.
1 meter (m)	=	3.28 ft or 39.4 in.
1 cubic meter (m^3)	=	1.307 yd^3
1 megapascal (MPa)	=	145.03 psi
1 gigapascal (GPa)	=	145030 psi
1 gram (g)	=	0.00220 lbm
1 kilogram (kg)	=	2.20 lbm
1 metric ton (mt)	=	2.20 x 10^3 lbm or 1.1tons
1 kilonewton (kN)	=	225 lbf
1 meganewton (MN)	=	225000 lbf
1 newton-meter (N-m)	=	0.737 ft-lbf
1 kilowatt (kW)	=	1.34 hp

APPENDIX D

Information from the Reference Information Base Used in this Report

This report contains the following information from the Reference Information Base.

TABLE D-1

UNIAXIAL COMPRESSIVE STRENGTHS USED FOR PERFORMANCE EVALUATION

THERMOMECHANICAL UNIT	COMPRESSIVE STRENGTH (psi / MPa)
TSw1 (LR - lithophysae rich)	2,350 / 16
TSw1 (GU-3 - litho. poor, well USW GU-3)	10,000 / 69
TSw1 (G-2 - litho. poor, well USW G-2)	25,380 / 175
TSw2	22,480 / 155
TSw3 (G-2 - well USW G-2)	7,540 / 52
TSw3 (G-4 - well USW G-4)	10,880 / 75
CHnlv	13,050 / 90
Chnlz	3,770 / 26

(TS - Topopah Spring, CH - CalicoHills, w - welded, n - nonwelded, v - vitric, z - zeolitized)

These values were obtained directly from RIB, Version 4, which was the current version at the time this report was submitted

Candidate Information for the Reference Information Base

This report contains candidate information for the Reference Information Base. A RIB Item should be drafted summarizing the results of this study on mechanical excavator performance predictions.

Candidate Information for the Site & Engineering Properties Data Base

This report contains candidate information for the Site and Engineering Properties Data Base. This information consists of physical properties test results and petrographic analysis of three welded tuffs.

END

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