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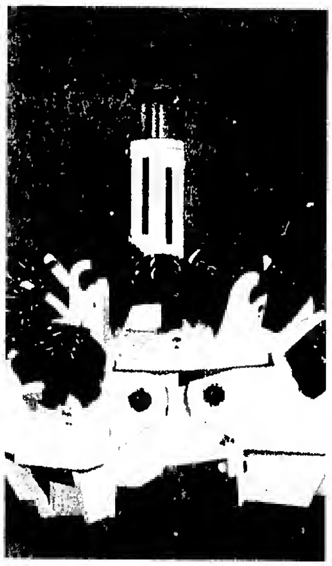

GEOTECHNICAL LABORATORY

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STATE-OF-THE-ART CONSTRUCTION TECHNOLOGY FOR DEEP TUNNELS AND SHAFTS IN ROCK

by

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This report describes the state of the art in construction technology for deep tunnels and shafts in rock. This study was part of the initial planning efforts for the deep-based missile system, but the methods described are applicable to a wide range of projects and conditions. As far as possible, all of the construction methods in this report are discussed from the point of view of production rates, costs, and appropriate conditions. All known methods for tunnel and shaft excavation, muck and material transport,
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support and lining, ground stabilization and ground-water control, and auxiliary operations are described herein.

General guidelines are given to assist in the selection of specific methods and equipment. Manufacturer's specifications and cost and performance data are included in the appendices to assist in this selection and to support the statements and conclusions made in this report.

EXECUTIVE SUMMARY

Background

This study was part of the initial construction planning for the ICBM Deep Basing Deployment Concept and is also applicable to construction planning for the ICBM Closely Spaced Basing Concept. The Deep Basing Concept, if selected, will require construction of several hundred miles of tunnels and related facilities in a very short period. Because of the immense project size and critical time frame, the Air Force and supporting agencies responsible for concept evaluation have initiated several research studies aimed at determining the most feasible methods to construct such a facility. As part of this overall effort, the U. S. Army Corps of Engineers Missile Construction Office (CEMCO) in support of the Air Force Regional Civil Engineer for Ballistic Missile Support (AFRCE-BMS) and the Air Force Ballistic Missile Office (BMO) requested that the U. S. Army Engineer Waterways Experiment Station (WES) conduct a study to determine the state of the art in tunnel and shaft construction technology. The study began 1 June 1982 and was completed 30 September 1982. The draft report, delivered in October 1982 was revised and updated for publication in September 1983.

Because of the extremely short time frame, as well as the sponsor's stated and perceived needs, it was decided early in the study to limit consideration to tunnel and shaft technology that has known or potential application to the Deep Basing scenarios previously developed by others and the general range of site conditions considered as acceptable for constructing such a facility. Consequently, this study has focused on methods and equipment suitable for construction of deep tunnels and shafts in rock.

The approach for this study consisted of: (1) review of background information on deep basing concepts and requirements, including general siting considerations; (2) extensive literature search and review, focused on tunnel and shaft construction methods; (3) consultation with recognized tunneling experts and equipment manufacturers; and (4) preparation of a state-of-the-art report on tunnel and shaft construction technology. The report is summarized in the following paragraphs, by major headings.

Tunnels

Only two methods are extensively used for driving rock tunnels: the drill and blast, and machine tunneling methods. Wide variations in practice exist for each of these general methods, depending on geological conditions, owner requirements, contractor preferences, and other factors. Drill and blast excavation has been the method by which all others have been judged for driving tunnels through rock. This method is quite versatile and can be readily adapted for changing rock conditions, an obvious advantage over full-face tunnel boring machines (TBM's) which depend on uniform conditions for good progress. Partial-face machines (roadheaders or digger shields) are more adaptable to changing ground conditions but are limited to use in soft to moderately strong rocks. The drill and blast method also enjoys the advantage over machine-driven tunnels of much lower capital costs for equipment. In drill and blast tunnels, the working room at the face is adequate for dealing with adverse conditions as they arise. Although access is not a problem with partial-face machine-driven tunnels, access to the face of TBM driven tunnels is usually severely limited; the machine occupies the entire cross-sectional area of the face. Consequently, probe drilling ahead of the face and changing cutter bits or bearings on the machine can cause disruptions because the machine must be stopped and backed away from the face. More recently, TBM manufacturers have made provisions in some machines for probe drilling through a central pilot hole in the machine's face, so excavation does not have to be halted. Another problem that has been dealt with effectively by some machine manufacturers is the installation of supports. Boring machines occupy virtually the entire tunnel cross section for 60 ft or more behind the face. Early versions had no provisions for installing support until the machine had passed. Squeezing or swelling rock or loose blocks falling from the roof or face presented major problems when encountered. Some recent machines have included provisions for rock-bolt installation and grouting and shotcreting very near the face through openings in the roof shield just behind the cutterhead. In addition, a few recent machines have provisions for maintaining face stability. A series of concentric ring beams may be mounted on the cutterhead to decrease the free air space between the rock and cutterhead and prevent loose blocks from sliding out and jamming the machine.

Until recently, drill and blast excavation was the method for driving tunnels through hard rock. TBM's could not effectively excavate hard rock. Partial-face machines still cannot do so because of their limited thrust capabilities. However, research into improved components and their arrangement to allow installation of supports, improved cutterhead design, cutter bits and bearings, hydraulics, and other areas have paid off for machine manufacturers and today, fullface boring machines are being produced that can be effectively used in very hard rock and difficult ground, making them quite competitive with drill and blast excavation.

These improvements have led to a sizeable increase in the share of TBM driven tunnels in rock. The historic advantages of drill and blast methods for hard rock excavation have been challenged and met by modern tunnel boring machines. Today these machines are being used to bore tunnels through a wide range of ground conditions. Tunnels have been bored up to 45 degrees upgrade, to 15 degrees downgrade, and sizes have ranged from 6 ft to over 35 ft in diameter.

In uniform, moderately strong rock TBM's have routinely averaged 50 to 70 ft/day and in several cases average rates have been over 100 ft/day. A good day's advance with drill and blast might be 70 ft/day, and average about 40 ft/day through similar rock. On the other hand, capital cost of a 16-ft-diam TBM might be $4 million or several times the cost of a drill jumbo for the same size job. Lead times for manufacture of a TBM are about 1 year, so this delay must also be considered. Therefore, for a TBM to be competitive with drill and blast, the tunnel alignment must be in favorable ground of sufficient length for the faster, more efficient TBM operation to offset its high capital cost. An often quoted figure for the break-even point is 1 mile, but as more used machines have become available, this figure has decreased. In some instances, tunnels as short as 1/4 mile have been economically driven with an available and suitable used machine. Often TBM's have successfully bored through short zones of very hard rock or blocky ground or water-bearing zones. However, progress is usually quite slow. If the entire tunnel alignment was in such unfavorable rock, the method would not be competitive. The TBM's advantage in advance rates is lost under such conditions because of the time required for control measures. Support installation and groundwater control set the overall pace of construction, not the excavation rate in these circumstances.

Similarly, very small tunnels impose constraints on the rates at which the excavated material can be removed from the face. Small muck loading and hauling units must be used that may not be able to keep up with the TBM. Muck hauling thus sets the overall pace of construction.

Thus, the choice of excavation method now requires detailed analysis of many factors; among them equipment capital costs, labor requirements and availability, owner requirements, project size, machine delivery lead times, site considerations, geological considerations, and geometry constraints.

Cook and Harvey (1974) and Fogelson (1974) have given a review and appraisal of the various innovative fragmentation and excavation methods including most of those presented in this report and also evaluated them in terms of standard techniques such as TBM and drill and blast methods. Overall, the relative or absolute effectiveness of a given method must be considered in terms of advance rate which is controlled by the following relation:

$$R = 3{,}600\ P/S$$

where

R = penetration rate, m/h

P = specific power delivered to the face, MW/m^2

S = specific energy, MJ/m^3

The specific energy is that consumed to break originally solid rock. Plots of specific energy versus grain size of fragmented rock produced can be made which show an inverse exponential straight line relationship between these two given quantities for a given rock. However, such plots yield two curves; one curve represents techniques which excavate and the other techniques which comminute or grind up the rock. Specific energy for excavation increases as fragment size decreases.

Cook and Harvey compare the effects of specific power and specific energy for drilling and conventional drill and blast tunneling using the example below:

	Diamond Drilling	Drill and Blast Tunneling
Specific energy	1,120 MJ/m^3	5.7 MJ/m^3
Specific power	3.8 MW/m^2	1.3 KW/m^2
Penetration rate	12 m/h	0.83 m/h

The tabulated data show that, in this example, the penetration rates are within an order of magnitude; whereas, both the specific power and specific energy of drill and blast tunneling are several orders of magnitude less than those values for diamond drilling.

Similar data for a variety of TBM's operating in a wide range of rock conditions are tabulated below:

Specific energy	18 - 420 MJ/m^3
Specific power	25 - 54 KW/m^2
Penetration rate	0.3 - 5.2 m/h

The data above show that TBM's exhibit a higher penetration rate over drill and blast accompanied by an increase in both specific energy and power over drill and blast; however, the increase in specific energy and power is significantly less than that of diamond drilling. From these examples, it is apparent that for any novel excavation method to be competitive with either drill and blast or TBM's the specific energies and powers of these methods must be similar to that of drill and blast or TBM.

Grantmyre and Hawkes (1975) reported specific energies for high-energy, mechanical impactors in the range of approximately 8-165 MJ/m^3 which is in the same range as TBM and drill and blast. However, there are limitations in hammer velocity, weight, and size of the impactors which affects power development, particularly in a tunnel.

Cook and Harvey (1974) give specific energy data for water-jetting which range from 0.3 x 10^3 to 33 x 10^3 MJ/m^3, significantly higher than either TBM or drill and blast. Similar relations are evident for thermal techniques including lasers and electron beams; however, at least with electron beams, spalling may be more efficient than cutting.

The relations between penetration rate, specific power, and specific energy for conventional and novel methods illustrate the requirement for high specific power for novel methods. Considering these relations, the applications of many of the novel methods are severely limited to secondary roles in tunnel excavation or to hybrid methods in which they are used to assist a conventional method. Even in secondary roles, use of some of these techniques would require modification of safety and health regulations of several Federal and State Regulatory Agencies. One exception is the use of water jet-assisted tunnel boring, which has shown significant potential for increasing production rates and decreasing costs.

Shafts

Most United States shafts have been sunk by the conventional method, i.e., drilling, blasting, loading, and hoisting the broken rock to the surface. Drilling is done by hand-held sinker drills or multiple drill jumbos. Several muck loading systems have been developed that are particularly adapted to shaft sinking, but muck hoisting is usually done with a bucket-cable-hoist combination. Sinking rates vary from about 70 to 300 ft/month in the United States. Low rates are usually a result of deep overburden, high inflows, incompetent ground, equipment breakdown, labor problems, poor supervision, or an inexperienced crew. However, conventional shaft sinking is relatively flexible, can cope with high water inflows and poor ground, and is a highly reliable method under most conditions. Compared with other shaft sinking methods, capital costs are low and labor costs are high since operation requires different skills but relatively simple equipment. Skilled shaft sinkers are becoming increasingly scarce. Costs vary widely depending on conditions, i.e., size, depth, location, and ground conditions. An impactor, developed by the U. S. Bureau of Mines, substitutes for drilling and blasting and has shown its potential ability to cut costs and speed up development. The techniques for inclined shafts are similar to those of vertical shaft sinking. No new techniques or equipment are available that could markedly increase conventional shaft sinking rates.

Conventional drill and blast shaft raising is used mainly for short shafts connecting mine levels. Muck removal is by gravity. Support may consist of timbered sets with a concrete lining installed after excavation is completed. Ventilation is difficult because the warmer smoke and fumes rise above the cooler air in completed segments of the shaft. This problem and falling rock make working conditions more hazardous than shaft sinking. However, conventional shaft raising is nearly twice as fast as conventional shaft sinking because the mucking cycle is eliminated.

Raise boring is a system for boring to the surface from a mine level or between mine levels. A pilot hole is first drilled and then enlarged by a machine mounted on the surface which pulls and turns a cutterhead mounted at the end of the drill rod. A disadvantage is that both the top and bottom of the shaft must be accessible and the depth of the shaft which it can bore is limited. However, it is a relatively safe, low-cost method. Several blind raise borers (boxhole drills) have been built. These machines push the cutterhead from below, without a pilot hole, but the shaft height is limited to about 300 ft. Raise boring costs are about half of conventional sinking and about two-thirds of large-diameter drilling. The largest existing raise borers can bore shafts 18 to 20 ft in diam to 1,000 ft deep, or smaller diameter shafts to greater depths.

Large-diameter drilling uses oil well drilling technology. Shafts over 10 ft diam have been drilled but the method is best for smaller diameters. Only vertical shafts can be drilled in the larger diameters. No underground miners are required because drilling and muck removal are handled on the surface. About two dozen United States drill rigs currently have the capacity to drill large-diameter shafts, and many well-trained crews are available. The principle disadvantage is the slow penetration rate for large-diameter shafts in hard ground, partly because of the poor muck removal rates. The cost of rigs capable of drilling 10-ft-diam shafts is about $50,000/day, overall, but rigs for larger diameter holes can cost more. The equipment is easily maintained, very reliable, and able to drill continuously. The linings have always been welded steel casings designed for full hydrostatic pressures, which are very expensive, accounting for up to 2/3 of the shaft cost.

Reaming may be used when access exists at both ends of a planned shaft to successively enlarge a pilot hole to the desired diameter. First a small diameter (12 in.±) hole is sunk to the opening below the shaft. A larger diameter cutterhead is then attached to the drill string and pulled up the shaft. Cuttings fall to the bottom and are removed as the shaft is enlarged. A special adaptation of this method is the use of the Wirth V-Mole, developed by the West Germans for use in existing coal mines. With this method, a 12-in. pilot hole is drilled as before, enlarged to 5 to 8 ft diameter by raise boring, and then the V-Mole enlarges the shaft to the desired diameter by boring from the surface downward. Cuttings fall through the pilot shaft to the workings below. This method has been successfully used in West Germany and in Alabama. At the Alabama site four, 23-ft-diam shafts were sunk by Thyssen to depths of 1670 to 2040 ft in record times, using a third-generation V-Mole.

A blind shaft borer is essentially a TBM that has been modified to bore vertically. A rotating cutterhead with roller cutters breaks the rock. In order for the borer to reach its potential for rapid development, a special system must pick up the muck from the face and transport it to the surface, but these systems have generally been inadequate. A European test on a hydraulic system, and a mechanical system used on a government-sponsored blind shaft borer development project have both performed poorly. A combination vacuum-pickup, air-transport system was tested and appears the best, but it has not yet been used in the field. System reliability and maintainability are poor but can be improved to match that of a tunnel borer. The main advantage of the blind shaft borer would be a sinking rate up to four times faster than with conventional shaft sinking at a comparable cost.

Muck Handling

Muck handling may be accomplished by rail-mounted systems, rubber-tired, or crawler-mounted equipment, conveyors, or pipelines.

Rail systems are used extensively in mines and tunnels. High capacity, high reliability, and low energy costs per unit volume moved are well-known advantages of muck trains. High capital and installation costs offset these advantages in short tunnels. Trains can be electric, diesel, or supplemental battery-trolley powered. Rail haulage is restricted to grades of 0 to 3 percent, unless a cable-assisted system is used. A separate loader is required and may be a conveyor or rail-mounted mucker or rubber-tired or crawler loader. Some rail muck cars are self-dumping; others require dump assistance.

Rubber-tired muck handling systems may consist of rubber-tired loaders and trucks, load, haul, dump units (LHD's), or combinations of LHD's and trucks.

Rubber-tired systems are versatile and can be used for hauling muck and transporting men and materials on varying grades up to 27 percent or so if a concrete roadbed is provided. Maximum grades of about 12 percent may be negotiated if the roadbed is not concrete. Extensibility of truck systems is inherent, no extensions to rail or utilities is required. Because trucks are diesel powered, high ventilation requirements limit their use in long tunnels, especially small-diameter tunnels. In small-diameter tunnels there is insufficient clearance for the ventilation lines. In tunnels below 12 ft diam, there is not enough clearance to load trucks. In such cases, LHD's may be used effectively for haul distances up to 7000 ft or so. This distance can be extended if rehandling stations are used. LHD's are slower than trucks (maximum operating speeds are about 30 mph for trucks and about 12 mph for LHD's) and capacities are lower, ranging from about 1 to 15 yd^3 for LHD's. Truck capacities range from 25 to 50 yd^3. These capacities are considerably less than rail systems, but much shorter travel times for trucks offset this disadvantage.

Crawler loaders can be used in wet headings where the invert is in poor condition. Crawler equipment is too slow for haulage.

Conveyors are used extensively in mines as total muck handling systems. In tunnels conveyors are used primarily for muck loading only. Conveyor systems are high capacity, very reliable, and simple to repair. Conveyors have high capital and installation costs, a disadvantage for tunneling. In addition, extension of the system to keep pace with excavation usually causes some delays, which can be minimized by the use of extensible belt conveyors. Conveyors can be used in virtually any size tunnel; maximum grade is limited to about 20° or 45 percent, up or down. Maximum muck size should be less than about 12 in. Power requirements are low; conveyors are efficient materials handling systems. In open pit and underground mines conveyors have been shown to have much lower life-cycle operating costs than trucks. But if one component breaks down, the entire system must be stopped until repaired. Separate means must be provided for transport of men and materials. Wet, sticky muck can cause problems with conveyors. Dust is a problem in dry headings, but dust is a problem with any muck handling system. Conveyors are powered by electric motors so ventilation is not a problem, except for the dust.

Pipeline muck handling systems have seen limited use in tunnels and shafts. Their use in coal mining has been increasing in recent years. The muck transport medium may be water or air. The systems generally consist of a muck crusher, a feed bin and feeder, pipe, elbows, and pipe supports, and blowers or compressors for air systems or pumps for slurry systems. Muck size and transport distances are very important considerations. Moisture content is critical for air systems. If the material is very wet, power requirements are higher and sticky fines may plug the pipe. Repairs require that the system be shut down, and with slurry systems, the pipes must be emptied before repairs can be made and before the system can be extended. A water supply and settling basins must be provided for slurry systems. Pipeline slurry systems have been used to advantage with hydraulic erosion tunneling in weakly-cemented St. Peter sandstone in the Minneapolis-St. Paul area. As with conveyors, of course, separate means must be provided for transport of men and materials.

Muck loading in shafts may be accomplished with clamshell diggers or track-mounted equipment. Shafts sunk by the impactor method rely on the backhoe attached to the galloway frame. Muck loading is not required for large diameter drilling or for conventionally raised or raise bored or reamed shafts. Muck loading problems have been the main obstacle to successful use of the blind shaft borer. Bucket elevators were tried with the Robbins borer and performed poorly. A pneumatic pipeline system has been tested and shows promise. A hydraulic pickup and hoisting system was used with the Wirth blind shaft borer.

Muck hoisting in shafts is often done with a headframe, winch, cable, and skip system. Pneumatic or hydraulic pipeline systems have seen limited use. Bucket elevators have also been used. Reverse circulation of drilling fluid is used to remove cuttings from large diameter drilled shafts. Direct or reverse circulation is used to remove cuttings from the pilot holes for reamed shafts.

Support and Lining

Support may be provided to stabilize the tunnel or shaft opening using any of several methods. Support design is largely empirical. Versatile support design is based on use of a single support method throughout the tunnel that is capable of supporting the excavation under the worst conditions expected. Adaptable support design is based on use of a range of support measures, keyed to the rock conditions encountered in each zone. Versatile support is more conservative in the zones of better rock, and hence, more costly for material. However, only one support system must be stockpiled and the crew quickly becomes proficient in installing a single system. Adaptable supports require stockpiling of several support systems and crew efficiency usually decreases after every change. However, material costs will be lower.

Soft ground support systems include steel ribs and lagging, cast-in-place concrete, precast concrete segmental lining, cast iron segmental linings, and steel segmental or rolled plate liners. Shotcrete is used and extruded concrete linings have seen limited use. Cast iron and steel are very effective liners but cost far more than concrete. In most cases, cast-in-place concrete and precast linings belong in the category of versatile support, i.e., they are designed for the worst conditions and are overconservative throughout the rest of the tunnel. Shotcrete is quite adaptable, but if a single thickness is specified in the contract, the advantage of adaptability is lost. Shotcrete may be used effectively and economically to protect steel support, to prevent initial deformations and loosening, or with rock bolts as a complete support system. Because of their high cost, cast iron and steel liners are only used under special conditions. Concrete can be used effectively for a range of ground conditions, from thin precast segments for aesthetics or improved flow properties, to thick cast-in-place linings to carry heavy loads and resist earthquake or blast damage.

Rock support systems include rock reinforcement and direct structural support. Rock reinforcement may consist of rock bolts, dowels, or anchors, and shotcrete. Steel ribs and lagging or concrete, either cast in place or precast segments, may be used for direct structural support. Rock reinforcement design is based on the concept of limiting deformations to take advantage of the rock's self-supporting ability. Rock bolts and/or shotcrete may be installed close to the face to limit deformations and this practice is recommended. Rock bolts and shotcrete are readily adaptable to changing conditions. Concrete linings must be installed some distance back from the face, which can result in problems in bad ground. Steel sets and lagging may be installed near the face in blasted tunnels. They are adaptable by varying spacing and support weight. Rock bolting and shotcreting can be integrated into the excavation cycle for TBM or drill and blast tunnels and should be placed under the control of a support specialist for best results. Installation of precast or extruded cast-in-place linings may also be integrated into the excavation cycle for TBM driven tunnels.

Nearly all shafts require support, which is usually provided by timber, steel, or concrete. Nearly all modern shafts are lined with concrete because it not only provides support but helps control groundwater and protects the wall rock from deterioration. More recently, shotcrete and concrete segments have been used. Welded steel liners are very effective in providing structural support while preventing water inflow, but their cost is high.

Shallow shafts or deeper shafts in competent rock can be lined after sinking, but most are lined concurrently with sinking. Support and lining costs are dependent on materials used, method used, geographical location, thickness of lining, and amount of groundwater.

Ground Stabilization and Groundwater Control

In some cases, ground conditions along the alignment of the tunnel or shaft may be so unfavorable that excavation cannot proceed without measures being taken to control and improve the ground. Such conditions are likely if the tunnel is being driven through unconsolidated sediments below the water table or in shear or fault zones in rock tunnels.

Pumping, grouting, freezing, and compressed air are the control methods available. A common feature of all these measures is high cost. Pumping and freezing are applicable in shallow tunnels.

Pumping is perhaps the least expensive alternative, but it can lead to subsidence and damage to surface structures and buried utilities, unless carefully executed.

Freezing is reliable, but expensive and slow. Freezing may be done from the surface using vertical brine or liquid nitrogen circulation tubes driven to tunnel grade. At greater depths the tubes may be driven in horizontally from the tunnel face. Freezing is quite expensive and is usually considered only if other methods cannot be used.

Grouting is used both to reduce inflows and to stabilize the ground. The fluid grout is injected under pressure into the mass to displace water and air in the voids. Once injected, the grout forms a gel or solid that decreases the coefficient of permeability and increases the effective shear strength of the mass. Several types of grouting materials and methods have been devised for different applications, including injection of portland cement, bentonite, and chemical grouts. Grouting may be done from the surface for relatively shallow tunnels or from the tunnel itself for deep tunnels. Where bad conditions are expected throughout the tunnel, a pilot tunnel may first be driven inside the main tunnel cross section and used for grouting operations ahead of the main tunnel excavation.

Compressed air may be used in soft ground tunnels below the water table. With this method, the excavation is stabilized by applying air pressure above atmospheric against the face to balance the excess hydrostatic pressures. Air locks must be installed back from the face or at the portal for passage of men and materials and muck. Working hours are reduced by law, depending on the working pressure. Progress is usually slowed significantly if compressed air must be used, both because of reduced working hours per shift and the added complexity in the muck and materials handling cycle. Compressed air tunneling is expensive, slow, and dangerous and is used only when required by unstable ground conditions. Recently, earth pressure-balanced, shield boring machines have been successfully introduced by the Japanese which may make compressed air a rarely used control method.

Ventilation

Forced air ventilation is required to remove dust, fumes, gases, and heat from the work area. Portals or shafts may serve as the fresh air inlet. Most modern ventilation systems are designed to allow reversal of the air flow through the ducts suspended from the roof. Systems used in drill and blast tunnels should be capable of exhausting explosives fumes and dust within 10 to 20 minutes so work can proceed. Development of in line blowers and site fabricated ducting have improved ventilation system performance and decreased costs, compared to prefabricated pipe. Collapsible plastic tubing may be used in positive pressure systems.

Hazards and Health and Safety Regulations

Control of recognized hazards in tunnels and shafts must include provisions for removal of dust and gases, supply of fresh air, noise reduction or hearing protection, equipment safety, fire protection, ground support, and instrumentation and monitoring to detect unsafe conditions. Such provisions are covered under various Federal and State mining safety and work regulations which must be followed. These regulations are cited in Part VII.

Instrumentation and Monitoring

Instrumentation and monitoring are required to detect unsafe conditions, such as roof instability, overstress in supports, or convergence and heave.

Various instruments have been designed to measure convergence, loads on supports, and stresses in the rock mass, including load cells, extensometers, and stress gages.

Alignment and Grade Control

Alignment and grade must be continuously monitored during excavation. Developments in laser surveying techniques have made this job much easier. Lasers can be made explosion-proof and optical guides have been developed which allow alignment and grade control to be maintained around curves without moving the laser. In TBM driven tunnels, the TBM is kept on line and grade through the use of grid targets mounted on the front and back of the machine.

CONTENTS

PREFACE

The study reported herein was performed for the Air Force Ballistic Missile Office (BMO) and the Air Force Regional Civil Engineer for Ballistic Missile Support (AFRCE-BMS), through the Corps of Engineers Missile Construction Office (CEMCO) by the U. S. Army Engineer Waterways Experiment Station (WES) under Interagency Agreement No. E-87-82-7134, during the period 1 June-30 September 1982. The draft report was revised and edited for publication in September 1983.

This study was part of the initial construction planning for the ICBM Deep Basing Deployment Concept. The study is also applicable to construction planning for the ICBM Closely Spaced Basing Concept.

Captain John P. Selstrom was the AFRCE-BMS project manager; Mr. George R. Dunham was the CEMCO project manager. Mr. John C. Bowman was CEMCO technical monitor.

This study was performed by a multidisciplinary team consisting of the following individuals: Dr. D. M. Patrick, Messrs. P. A. Taylor, W. B. Groves, H. J. Smith, C. C. McAneny, and R. D. Bennett, the project manager and principal investigator, all of the WES Geotechnical Laboratory (GL), Engineering Geology and Rock Mechanics Division (EGRMD), Rock Mechanics Applications Group (RMAG), except Dr. Patrick of the Research Group.

Mr. J. S. Huie was Chief of RMAG during this study, Dr. D. C. Banks was Chief of EGRMD, and Dr. W. F. Marcuson III was Chief of GL.

COL Tilford C. Creel, CE, was Commander and Director of WES during the period of this study. Mr. F. R. Brown was Technical Director.

In addition to the WES team, the U. S. Bureau of Mines, Spokane Mining Research Center, provided technical assistance on this project through an interagency agreement. The USBM group, headed by Mr. Paul F. Sands, prepared the draft section on shaft construction methods and equipment. Other members of this group included Dr. Michael Sokaski, Messrs. Alan Wilson, Duane Jones, Michael Beus, Grant Anderson, and Ms. Elaine Bowers. Mr. Douglas Bolstad was Director of the Spokane Mining Research Center during this study.

Dr. John Hignett, Camborne School of Mines, UK, provided valuable technical assistance, especially in the areas of machine driven tunneling technology and ground support.

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Dr. Z. T. Bieniawski, Pennsylvania State University, reviewed the draft and provided several helpful comments on support design, machine tunneling experience, and other topics.

Special thanks go to Mrs. Vicky Bryant for her patience and hard work in typing this report. The Technical Information Center staff at WES, including Mmes. Terry Kiss, Kathleen Barnes, Deborah Carpenter, and Carol McMillin, did a tremendous job of obtaining the required technical literature for this study in a very short time.

Since completion of the draft report in 1982, there have been numerous requests for copies by other Corps offices, other Federal agencies, universities, and private organizations.

The sponsoring agency (AFRCE-BMS) declined to fund publication but gave permission to the Corps to publish and distribute the report.

The Office, Chief of Engineers (OCE) agreed to fund publication because of the continuing interest shown by the technical community and because it would be a valuable reference document for other Corps offices.

Publication was funded under OCE Civil Works Investigation Study (CWIS) 31700, "Special Studies in Rock Mechanics."

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement may be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.873	square metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
foot-pounds (force)	1.3355818	newton metres
gallons (U. S. liquid)	3.785412	cubic decimetres
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	2.54	centimetres
kips (force) per square inch	6.894757	megapascals
miles (U. S. statute)	1.609347	kilometres
pounds (force)	4.448222	newtons
pounds (force) per square inch	6894.757	pascals
pounds (mass) per ton (2000 pounds, mass)	0.5	grams per kilogram
tons (force)	8896.444	newtons
tons (2000 pounds, mass)	907.1847	kilograms

STATE-OF-THE-ART CONSTRUCTION TECHNOLOGY FOR DEEP TUNNELS AND SHAFTS IN ROCK

PART I: INTRODUCTION

Background

1. An announcement is expected sometime in the near future on the selection of a long-term deployment concept for the Intercontinental Ballistic Missile (ICBM). Meanwhile, various basing concepts have been identified and are being studied to provide the necessary technical and cost feasibility of each concept so a rational decision can be reached. One such concept is the so-called deep basing (DB) concept, in which the missiles would be deployed in deep underground tunnels, invulnerable to enemy first attack and available for retaliatory attack. This concept, if selected, will require construction of several hundred miles* of tunnels and related facilities in a very short time if the Initial Operating Capability (IOC) deadline of 1989 is to be met. Because of the immense project size and critical time frame if this concept is adopted, the U. S. Air Force and supporting agencies responsible for DB concept evaluation have initiated several research studies aimed at determining the most feasible methods, technically and economically, to construct such a facility. As part of this overall effort to evaluate the DB concept, the U. S. Army Corps of Engineers Missile Construction Office (CEMCO), in support of the Air Force, requested that the U. S. Army Engineer Waterways Experiment Station (WES) conduct a study to determine the state of the art in tunnel and shaft construction technology. The study began 1 June 1982 and was completed 30 September 1982.

2. Because of this extremely short time frame, as well as the sponsors' perceived and stated needs, it was decided early in the study to limit consideration to tunnel and shaft technology that has known or potential application to the DB scenarios previously developed by others and the general range of site geological conditions considered as acceptable for constructing such

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 20.

a facility. Information furnished by CEMCO and others* (Boeing Co., 1980; Clark, Ozdemir, and Wang, 1980; Oberste-Lehn, 1980; Mnew, 1981; TRW, 1982; and U. S. National Committee on Tunneling Technology, 1982) was reviewed to provide the needed focus for this study. The practical consequences of this preliminary review were that this study has focused on methods and equipment suitable for construction of deep tunnels and shafts in rock.

Purpose

3. The purpose of this study was to determine and to report to the sponsor the state of the art in tunnel and shaft construction technology.

4. The overall purpose of this study and related efforts has been to provide the decisionmakers with the technical and cost feasibility information required for a rational choice among the various basing options being considered for deployment of strategic defense missiles.

Approach

5. The technical approach for this investigation consisted of:

- a. Preliminary review of literature furnished by CEMCO and others (Boeing, 1980; Clark, Ozdemir, and Wang, 1980; Oberste-Lehn, 1980; Mnew, 1981; TRW, 1982; and U. S. National Committee on Tunneling Technology, 1982) on DB concepts and geological and other site considerations and requirements to provide a focus for the subsequent state-of-the-art review.
- b. Extensive literature search and review process, focused on excavation and muck-handling technology (methods and equipment) appropriate for construction of deep tunnels and shafts in rock. Auxiliary and support operations and equipment were also considered.
- c. Consultation with recognized experts in tunnel and shaft construction technology, and telephone contacts and personal visits with tunnel and shaft equipment manufacturers.
- d. Identification of emerging technology and critical problem areas that could influence construction of a DB facility.
- e. Preparation of a state-of-the-art report on tunnel and shaft construction technology.

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* Personal communication, J. Broughton, U. S. Army Engineer Waterways Experiment Station, June 1982.

Scope

6. As stated previously, time did not permit, nor was there a perceived need, to report on every possible construction method that could be used for all possible site conditions and end uses. Consequently, this report describes only those methods and machines with known or potential applications to construction of deep tunnels and shafts in rock. However, soft ground tunneling methods were summarized because of the possible consequences of encountering mixed face conditions, crushed rock zones, and soft ground during construction of rock access and egress tunnels and shafts. The impact of and methods for mitigating the above conditions and other problems such as unexpected groundwater inflows were considered and are reported herein.

7. This report has been organized as follows: Part I gives the background, purpose, approach, and scope of this investigation and report. Excavation methods and equipment currently used in driving rock tunnels are described and compared in Part II. Novel excavation methods are also discussed in Part II. Part III is a parallel discussion of shaft construction technology. Muck handling systems are discussed and compared in Part IV. Support and lining considerations are discussed in Part V. Part VI describes ground stabilization and groundwater control measures. Auxiliary operations are discussed in Part VII. Conclusions and Recommendations are given in Part VIII. Manufacturers' specifications, a list of contacts, cost and performance data from selected tunnel projects, and a glossary of terms used in this report have been compiled in Appendices A-D, respectively.

PART II: TUNNEL CONSTRUCTION METHODS AND EQUIPMENT

8. Methods and equipment used to construct tunnels in rock are described in this section. The only extensively used methods for tunneling through rock are drill and blast and full-face tunnel boring machine (TBM) excavation. Partial-face machines have been used in Europe but have seen only limited use in the United States. Novel excavation methods are briefly summarized but are not considered practical for most applications. Regardless of the excavation method used, access must be provided to the tunnel elevation. Depending on site topography and the intended use of the tunnel, access may be provided by means of a shaft or portal. Shaft construction methods are described in Part III. Portal excavation is summarized in the following paragraphs.

Portal Excavation

9. If the tunnel is to begin or terminate at a portal, open-cut excavation is required for this section. Long-term stability of the side slopes and overlying region must be ensured by adhering to sound soil and rock mechanics design principles.

10. Overburden soils are usually removed by bulldozers or scrapers down to bedrock. The rock may then be ripped or blasted down to a berm above the portal. Once the rock berm is constructed, vertical anchors can be installed if needed. These anchors, when used, are normally placed just downstream from the portal face and extend to just above the tunnel crown. For a single tunnel, three or four rows of anchors spaced 4 to 5 ft apart can be used. The rows would extend around and include a portion of the sides of the portal. The portal face is then excavated. When the face is to be rock bolted, the bolts should be placed as each lift is excavated. If a portal canopy or a portal structure is required, it should be constructed as soon as possible after the face excavation is completed. When excavating in a portal area, controlled blasting should be required. Controlled blasting can be accomplished by either presplitting, smooth blasting, or line drilling. A description of the procedures used to obtain sound rock walls is explained in EM 1110-2-3800 (U. S. Army Corps of Engineers, 1972), and should be consulted when excavating portals. The first pull of the tunnel at the portal should be

limited to 3 to 4 ft using light blasting charges to prevent damage to the portal rock or the concrete portal structure. Line drilling or presplitting of the crown and sides can also be used if conditions warrant. The length of round and powder factor is then gradually increased as the distance from the portal increases.

Drill and Blast Excavation

11. Conventional or drill and blast excavation has been the method by which all others have been judged for driving tunnels through rock. This method is quite versatile and can be readily adapted for changing rock conditions.

Description of method

12. Drill and blast excavation is characterized as a series of cyclic operations, as opposed to the nearly continuous TBM excavation. A complete cycle is known as a round. The steps which comprise a complete cycle or round of drill and blast excavation are:

a. Drilling cycle. The drill jumbo is moved up to the face, and air or electric lines and waterlines are connected. Roof supports are installed if needed, to support the section from the previous round from the jumbo. In poor rock conditions, shotcrete must be applied before the jumbo is moved in, immediately after ventilation and before mucking in some cases. The blastholes are drilled on a predetermined pattern. The drill jumbo water and air or electric lines are then disconnected and the jumbo and work crew are moved back a safe distance from the face. The holes are then charged with explosives and electrical blasting caps and leads are attached by an explosives specialist.

b. Blasting cycle. The round is detonated, usually with short delays (delay time is normally 25 milliseconds) between blast rings to improve blasting efficiency. The face is then ventilated to remove smoke and fumes. The powder man then goes in to check for misfires and clears the tunnel.

c. Mucking cycle. After ventilation, the roof and the walls must be scaled and the fly rock cleaned up. Then the mucking machine is moved up to the face and loads the muck into the rail muck cars or rubber-tired trucks. The ventilation lines, water and air or electric lines, and the track (if rail-mounted equipment is used) must be extended periodically and the complete cycle is repeated. Depending on ground conditions, additional operations such as probe drilling ahead of the face, grouting ahead of the face for prevention of groundwater leakage, or forepoling (driving wooden spiles ahead of the face to support the roof) may be necessary before resuming another round of excavation. Drill and blast excavation leaves an uneven surface. Some rock may stick out inside the specified excavation dimension. These areas are known as "tights" and must be removed before any lining can be installed. This operation may be done using impactors or very light charges.

Heading advance options

13. Figure 1 shows several options for advancing the tunnel face by conventional excavation to accommodate special conditions. In poor quality rock or mixed face, or in very large tunnels or caverns, top heading and bench excavation or multiple-drift excavation may be used. Most modern tunnels are driven full face, whenever possible. When heading and bench excavation is used, the top heading is normally driven portal to portal before excavating the bench. This practice allows the use of one drill jumbo in both operations. Before jumbos became popular, the bench was usually excavated just behind the heading, with only a short (10 to 15 ft) working platform left, so that drilling the top heading and mucking the bench could proceed simultaneously.

14. Multiple drift excavation is used only in bad ground when the crown must be continuously supported or in very large excavations. Small drifts are driven at opposite spring lines and rock bolts are installed in a radial fan pattern from opposite drifts to intersect or overlap above the crown. Shotcrete may then be applied within the small drifts to prevent deterioration of the rock within the drifts. Alternatively, a method known as drifting for wall plates may be used in combination with heading and bench excavation. Again, small drifts are driven at opposite spring lines, and longitudinal beams are installed and anchored to the rock. The remainder of the top heading is then carefully excavated using small charges. Closely spaced steel arch ribs to support the rock are then erected, bearing on the wall plates, and the ribs are blocked in place. Wood lagging extends between the steel arch sets to prevent rockfalls between them. This method is used only in rock with very short stand-up time (rock requiring immediate support installation). Once the top heading is driven and supported, the bench may be excavated with much less danger because the miners are then working under a well-supported roof. There are variations in the placement and number of drifts to meet special conditions. For example, on a recent large-diameter tunnel in treacherous rock, a series of small-diameter drifts was driven around the entire circumference and backfilled with concrete before excavating the main tunnel.

This method will also be used on the 63-ft-diam Mt Baker Ridge Tunnel, to be built soon.

15. Mixed face excavation refers to a condition where part of the tunnel face (normally the roof and upper portion) must be driven through crushed rock or soft ground and the remainder must be driven through more competent rock. Soft-ground methods are used to excavate the top heading. Supports are installed closely behind the face and sharpened wooden spiles or interlocking steel channels are driven into the roof from behind the nearest steel set at a shallow upward angle and extend beyond the face to support the roof prior to continuing excavation. This practice is known as spiling or forepoling. Conventional drill and blast excavation may then be used to remove the bench.

Blasting patterns

16. Blasting patterns vary for different geological conditions, tunnel sizes and shapes, and because of contractor preferences. The many factors that should be considered to develop an efficient blasting pattern are discussed in detail in EM 1110-2-2901 (U. S. Army Corps of Engineers, 1978) and in the Blaster's Handbook (du Pont, 1977). Blast holes may be drilled to any depth from 6 to 15 ft or so but are normally drilled either 8 or 12 ft deep. In any lift, increasing the depth means increasing drilling time and powder factor because breakage is more difficult. The length of rock pulled is usually slightly less than the hole length; e.g., an 8-ft hole will pull about 7-1/2 ft of rock. The most efficient blasting pattern, hole depth and specific charging must be determined for each individual job and requires test blasting to attain best results. The number of rounds that can be driven per day, the length of round, ventilation capacity, mucking capacity, and several other factors must all be balanced to produce an efficient tunneling operation. The blasting pattern may have to be changed several times during the tunnel drive as conditions change. Empirical guidelines for selection of powder factor, hole diameter, spacing, and depth are given in the Blaster's Handbook.

17. Three popular blasting patterns are the pyramid or angled cut, the burn or parallel cut, and the V-plough cut. Figures 2a-2c show these blasting patterns. With the angled pattern, cut holes are drilled from the face at an angle to the axis and nearly intersect at the axis (Figure 2a). These holes are heavily charged with ammonium nitrate fuel oil (ANFO) or water gel. Next, a ring of relief or easer holes is drilled, followed by one or more rings of

enlarger holes, depending on the tunnel diameter. The outermost holes are called the trim holes. Trim holes in the invert are called lifters. Trim and lifter holes are loaded with lighter charges of a different explosive, such as Du Pont "Tovex 90," a low-density water gel designed to minimize overbreak and leave a relatively smooth profile. Successive rings of holes are detonated after predetermined delays, starting with the cut holes at the axis. Trim holes are fired last. The lifters in the invert may be fired before or after the trim holes around the crown and spring lines, depending on the desired shape of the muck pile. The muck in the center of this pattern tends to break into larger pieces than the rest of the face which makes mucking difficult. Also the muck pile is more scattered. There is also more potential for damage to ventilation lines and supply lines because the muck is thrown wider and further. The burn cut pattern uses one or more large-diameter (approximately 5 in.) uncharged holes at the axis to allow room for rock expansion when the outer rings are detonated. Again, blasting proceeds from the easer holes to the trim and lifter holes, usually with predetermined delays between detonations of successive rings (Figure 2b). The V-plow pattern allows several holes to be drilled from the same position. Shallow holes are drilled from a given distance from the axis and are inclined to intersect at the axis. The next ring of holes is drilled from the same position but is deeper and intersects at the axis further from the face than the first ring (Figure 2c). The burn cut pattern is the most common because it is easier for drillers to use; the burn cut and outer rings are all drilled perpendicular to the face. The angled cut pattern and V-plow pattern require slightly more time and skill for alignment. The angled cut or V-plow cut cannot be used in small headings because of the lack of room. The powder factor and drilling factors are lower for the angled cut but the length of round pulled is also lower than for the burn cut.

Equipment options

18. Nearly all drill and blast excavated tunnels make use of a drilling jumbo—a movable work platform with pneumatic or hydraulic drills mounted on articulating booms on the jumbo. Figures 3 and 4 are examples of modern drill jumbos. The jumbo is moved to and from the face on rails, crawlers, or rubber tires. The number of drills mounted on the jumbo depends on the cross sectional area of the tunnel and the desired drilling speed. It is normal to mount one or two drills for small tunnels or about four for large tunnels and

caverns, but up to seven or eight drills have been used on the largest jumbos for excavation of very large caverns. About the only exception to the use of jumbos for drill and blast excavation is in very small tunnels (less than about 8 ft in height) or in very bad ground where multiple-drift excavation is used. Even then, a jumbo may be used for the bench excavation. In very small tunnels jack-leg drills are used. These are lightweight drills that make use of an adjustable prop or leg to assist the miner in positioning and aligning the drill. A variation of this type drill is also used to install roof bolts. The equipment options for a drill and blast tunnel, including pneumatic, hydraulic, and water-jet drills, and drill jumbos and impactors are discussed in more detail in the following paragraphs.

19. Drills. The Rotary/Percussion (R/P) Drill was introduced to mining and tunneling in 1912 by Ingersoll-Rand (Stack, 1982). Today, there are many manufacturers of R/P drills, including Gardner-Denver, Chicago Pneumatic, Joy, Atlas Copco, and Tampella-Tamrock. Modern R/P drills are powered by either compressed air or high-pressure hydraulic pumps driven by electric motors.

20. While minor differences such as size and length of the piston or the particular type of valve action used may vary between manufacturers, pneumatic drills are basically similar in concept. The pneumatic drill is powered by compressed air, which is fed in turn first to the back and then to the front of a cylinder. This action causes a piston within the cylinder to reciprocate back and forth and strike a tool held in the chuck.

21. To keep the tool from jamming in the hole, it is necessary to rotate the drill bit slightly, using an air-driven rotation motor. These motors are built on either the front or back-head of the machine, and rotate the drill bit through a system of gears.

22. An important consideration with rock drills is lubrication. The three methods generally used are hand-oiling systems, oiling systems within the drill itself, and airline lubrication.

23. With hand-oiling, the oil is injected into the airline connection on the machine and is fed to the various moving parts of the drill by the air. Unless the operator inserts the oil regularly when required, the moving parts will wear rapidly.

24. Airline lubrication systems work well if positioned about 10 ft or less from the drilling machine. At this distance the oil is finely atomized and thus penetrates the moving parts properly. However, if the oiler is more

than 10 ft from the drill, the atomized oil forms droplets on the side of the pipe. These droplets are carried along by the air, but because it is no longer atomized the oil does not lubricate the drill efficiently.

25. Hydraulic drills were developed during the 1960's, and the first all-hydraulic jumbo was introduced by Montabert in 1970. This jumbo is still in operation and has drilled 2 million feet in eight years (Stack, 1982). During this time, it was only out of service for two months for overhaul and maintenance, so reliability has been excellent.

26. The all-hydraulic R/P drills are similar in concept to the compressed air drills. The hydraulic fluid is fed first into the front and then the rear chamber of a cylinder. This causes the piston to reciprocate back and forth and strike against a drill tool. The majority of the newer hydraulic drills use accumulators either in the rear chamber alone or in both the rear and front chambers. The accumulator in the rear chamber is designed to impart extra energy to the piston on the forward stroke. It consists of a nitrogen-filled compartment or chamber which is separated from the compartment containing hydraulic fluid by a flexible diaphragm. When the hydraulic fluid is pumped into the rear chamber, it also fills the accumulator oil reservoir which compresses the nitrogen gas in the compartment at the back of the rear chamber. As soon as the piston is thrust forward by the fluid in the main rear chamber, the nitrogen gas expands and pumps the oil in the reservoir into the main rear chamber, thus transferring the extra energy stored by the compressed nitrogen gas to the piston and the drill tool. The front accumulator cushions the drill against any high peak pressures that may be caused by erratic action of the piston when it is thrown forward. Front accumulators are not used in air drills because energy waves are absorbed by the compression of the air in the front chamber.

27. A disadvantage of all-hydraulic drills is their greater need for flushing water, which must be delivered at a higher pressure and in larger volume than is necessary with the compressed air drill. If water is not supplied in sufficient quantity and at the correct pressure, the drill bit might jam in the hole.

28. Hydraulic drills are becoming more popular because of the advantages over pneumatic drills listed below.

29. Comparison of hydraulic and pneumatic drills. Advantages of hydraulic drills over pneumatic drills include:

a. Penetration rates. Penetration rates are 50 to 100 percent greater than pneumatic drills.

b. Power requirements. Power requirements are only one-third to one-half that of an equivalent pneumatic drill.

c. Durability. Longer drill steel and bit life are obtained because the long slender piston hammer gives a better shape to the energy pulse as it travels down the drill steel after impact, and because the hammer produces a stress wave of lower amplitude than does the large-diameter piston of a pneumatic drill.

d. Improved environment. Use of hydraulic drills results in a better working environment because exhaust air problems are eliminated, reducing noise levels and the water, fog, and oil mist that are inherent with pneumatic drills.

Disadvantages of hydraulic drills include:

a. Cost. Hydraulic drills cost nearly twice as much as equivalent air drills.

b. Maintenance. Hydraulic drills are more sophisticated and maintenance procedures must be upgraded. A separate workshop must be provided for a dust-free maintenance environment.

c. Hydraulic oil must be kept extremely clean because internal valve clearances are only 5 to 10 microns. Sealed circuits and good filters must be used. Filters must be replaced at regular intervals.

d. Seals. Certain air leaks are acceptable in pneumatic drills, but significant hydraulic leaks are unacceptable in hydraulic drills for obvious reasons.

e. Operator skills. Personnel have to be more skilled to operate hydraulic equipment.

30. Some of the listed disadvantages can be overcome with care by keeping the fluid and equipment clean, by adhering to a good preventive maintenance program, and by training miners to use and properly maintain the hydraulic equipment. It has been noted that as drill and maintenance personnel become more familiar with the hydraulic drills, availability has gone up and maintenance costs have gone down. Availability during a large project in 1978 consistently averaged above 90 percent (Engineering News Record, 1982). With a strong preventive maintenance program, one of the world's largest jumbos made by Gardner-Denver, was used for the excavation of over 325,000 yd^3 of materials in eight months (November 1981 through July 1982), and had 100 percent availability. The initial higher cost of hydraulic equipment is offset by the reduced cost in bits and tool steel, less energy consumption, and more rapid penetration. Hydraulic drill specifications are given in Appendix A.

31. Water-jet drills. Water-jet drills have only been available since the late 1970's and have seen only limited use. The water-jet drill can be used to cut drill and blast holes, holes for rock anchors, and slotting. Figure 5 shows a water-jet jack-leg drill and the power pack required for the drill.

32. A few soft rock types can be cut at low pressure (below 20,000 psi), but because of variable rock conditions, higher pressures are generally used. Water-jet drills can operate at up to 35,000 psi with flexible hose, or 55,000 psi with articulated tubing. (For specifications on water-jet drills, see Appendix A, courtesy of Flow Industries.)

33. The major advantages of water-jet drills are that the shape of the hole can be varied, which is particularly helpful in rock bolting, and their penetration rates are higher than air drills. The major disadvantages are their low efficiency, and thus high power requirements, and the requirement for a large water supply.

34. Jumbos. A jumbo is basically a portable work platform with one or more movable boom-mounted drills (Figures 3 and 4). Rail-mounted jumbos are used for both drilling and installing supports. Booms may be mounted on the cherry picker or they can be mounted on a conveyor frame straddling the train track on its own tracks (gantry jumbo). The jumbo must be able to move to the face for drilling and away from the face for blasting and mucking. The jumbo may ride on separate tracks straddling the muck train tracks, or ride the train tracks (main-line jumbo). While blasting and mucking, the main line jumbo may be switched to an out-of-the-way position. The use of trains is uneconomical for haul distances of less than about 1 mile, which in turn limits the use of track jumbos.

35. Pneumatic and hydraulic drills also may be mounted on truck frames, crawler equipment, and special purpose rubber-tired equipment. The number of drills varies with job and is a function of the diameter of the tunnel, number of drill holes in the pattern which is a function of the geology, and the type of drill (hydraulic or pneumatic). A jumbo can be built on almost any type of chassis with as many drills as are needed for the job. In tunnels that have diameters less than 18 ft, a main-line drill jumbo is recommended. In tunnels with diameters that exceed 18 ft, either a main-line or gantry-type jumbo can be used. Whether the drill jumbo should be crawler-mounted, rubber-tired, or rail-mounted is controlled by the mode of travel of the muck haulage units and

the condition of the invert roadbed. Drill jumbo specifications are listed in Appendix A.

Explosives and blasting underground

36. General principles. The most important factor in any blast is proper blast design. This should be based on an understanding of the mechanics both of the explosion and of the rock's reaction.

37. The detonation of an explosive charge gives rise to two effects: shock and gas pressure. Both are important, but gas pressure is the more important effect in breaking rock. The stronger and more massive the rock, the greater is the importance of the shock effect; but even in the strongest rock, the gas-pressure effect probably dominates.

38. The shock generated by the detonation travels outward through the rock as a compressive strain pulse. When this pulse reaches a free surface, it is reflected back as a tensile pulse. Since rock is relatively weak in tension, it breaks. Surface spalling occurs at the free-surface point nearest an explosive charge as evidence of this effect.

39. The extremely fast chemical reaction of an explosion results in enormously compressed gases in the borehole. The gases expand and do useful work by forcing the walls of the borehole apart. The movement of the rock and the breakage that occurs as it moves are due to this gas-pressure effect.

40. In the first moments while the explosion gases are forcing the walls outward, tensile "hoop" stresses form in the walls and radial cracks form. These cracks propagate through a combination of sustained outward pressure and gas forcing its way into the cracks and expanding them.

41. Although radial cracks are important in initiating breakage, most of the breakage occurs as the rock moves away from the blast hole and in the process bends and contorts. For this reason the primary consideration in designing a blast is provision of a free face and a volume into which the rock can fall. If the rock cannot move, it cannot break. This fact must be kept in mind to design a blast successfully. (Blast patterns used in tunnel and shaft work are described elsewhere in this report.)

42. Any rock blast will be influenced by the geologic structure. Whatever the system of existing or incipient fractures at the site, breakage will take place preferentially along these fractures. If a strongly anisotropic geologic structure is present, the designer should try to anticipate its effects and allow for them. The site fracture pattern will also influence the size distribution of the blasted rock or muck.

43. Explosives and blasting agents. Explosives and blasting agents are characterized by a number of properties. Discussions of these properties may be found in du Pont, de Nemours and Co. (1977), EM 1110-2-3800 (U. S. Army Corps of Engineers, 1972), and Johnson (1971). Some of these are defined in the Glossary (Appendix D).

44. In addition to properties, one should be aware of the classification of explosives, in accordance with the Code of Federal Regulations. Four categories of explosive materials, in order of decreasing hazard, are Class A, Class B, and Class C explosives, and oxidizing materials. The more hazardous the material, the more restrictions surround its handling, and consequently the more expensive it is to transport. Dynamites are Class A explosives; blasting agents that contain no high explosive component are oxidizing materials. A discussion of explosive classification may be found in Johnson (1971).

45. One further classification established by the U. S. Bureau of Mines is that of "permissible" versus "nonpermissible" explosives. This refers specifically to coal mining, where common methane gas and fine coal dust both produce hazardously explosive atmospheres. Permissible explosives contain flame-depressant additives which reduce the risk of atmospheric explosions in mines.

46. An important factor in explosive selection is cost. As might be expected, there is a broad variation in the costs of explosive products, but one rule of thumb usually holds true: ANFO is unique in its low cost; generally half that of other products or less.

47. Selection. There are three major groups of explosives to choose from: dynamites, dry blasting agents, and wet blasting agents.

48. Dynamites are reliable explosives, which for many years were the only type of explosives used in quantity in underground blasting. Among the wide variety of dynamite products, some could always be found to offer excellent water resistance, or to meet other specific site problems. In the last two decades, however, dynamites have progressively decreased in importance as the development of blasting agents has led to cheaper and safer products that perform as well or almost as well as dynamite. In 1982, according to Richard A. Dick of the U. S. Bureau of Mines (personal communication), dynamites accounted for about 5 percent of the U. S. commercial explosives used. The chief disadvantage of dynamites is that they are Class A explosives and

are subject to accidental detonation from impact, heat, and friction. A lesser disadvantage is that they may produce severe nitroglycerine headaches among explosives handlers.

49. ANFO is the predominant dry blasting agent used. Crude ANFO can be made by mixing ammonium-nitrate fertilizer pellets with fuel oil, but commercial ammonium nitrate for blasting purposes is always used in the form of porous prills, which allow an intimate contact with the liquid fuel oil. ANFO can be purchased premixed and ready to use, or a mixing plant can be established at the jobsite. Economic considerations determine such a decision. The advantages of ANFO are its insensitivity, safety, ease of handling and shipping, and above all, its low cost. The disadvantages of ANFO include its low density and related low energy per unit of borehole volume, but above all its complete lack of water resistance. Ammonium nitrate is not only soluble but also hygroscopic, and even a moist atmosphere over an extended period will tend to degrade its performance. So advantageous is its price, however, that some large users of explosives, such as quarries and open-pit mines, rather than using higher-priced wet blasting agents, place a watertight sleeve in the borehole and fill it with ANFO. Another disadvantage of ANFO is that it is quite diameter-sensitive, and may not reliably detonate in a small-diameter blasthole. The prospective user of ANFO should satisfy himself that the product that he expects to use has been demonstrated to detonate reliably in the size of hole that he plans to drill.

50. The field of wet blasting agents is dynamically changing and it is not possible here to give other than very general guidance. The names Water Gel, Slurry, and Emulsion are used by various manufacturers, and as a first approximation, these may be regarded as synonymous. The advantages of the various products on the market are that, collectively, they overcome ANFO's problems with water, and relative to ANFO, they are denser and accordingly more powerful for a given volume of borehole. Various sensitivities, including those requiring auxiliary boosting and those that can be initiated simply with a cap, are available. There is probably no better advice than to talk to one or more reliable, experienced explosive suppliers and compare a given product's demonstrated performance under known conditions with the conditions that exist at a given job. The factor of fume class should be kept in mind for underground work, since the generation of hazardous gases in confined spaces leads to safety and ventilation problems. Because the field of wet

blasting agents is changing so rapidly, there is probably no source where an impartial review of all available types of products can be found.

51. Generally, stronger and more massive rock responds better to a high detonation-velocity explosive. A slow explosive in a well-designed blast, however, may produce better results than a faster explosive in a blast that was poorly designed.

52. Initiation systems. Almost as important as the explosive itself is the system used to detonate it. The basic initiating device is the blasting cap. There are fuse caps and electric caps, and among the latter there are instantaneous and delay caps. Any cap contains an ignition system. In an electric cap this involves a resistance element, while the fuse cap is ignited by a jet of flame. The ignition system fires a primer charge, which in turn fires a base charge. The latter is a small amount of a primary explosive, a substance highly susceptible to detonation even in very small quantities. The explosion of the base charge furnishes a shock that detonates the next unit in the explosive chain. This may be a booster charge or, in the case of cap-sensitive products, the main charge itself. Delay electric blasting caps contain a finite-burning delay element interposed between the ignition system and the primer charge. By this means, an electric signal may fire the ignition systems of a whole set of caps, but the caps' respective base charges will fire at instants determined by their respective delay elements.

53. The overall system available for firing may be classed as electric, newer nonelectric, and detonating cord. Electric systems are the most common, are subject to excellent control, and in the vast majority of situations are very safe. The only requirement to make this so is a careful analysis of the site situation and a careful design of the blasting circuitry. Du Pont, de Nemours and Co. (1977) and Atlas Powder Co. (1976) give detailed guidance for such analysis and design.

54. Two new nonelectric systems are Nonel and Hercudet (both trade names). The first uses a small plastic tubing with a powdered high explosive interior coating; the second uses plastic tubing into which an explosive gaseous mixture is pumped and then fired. Both are sophisticated systems and should be used only with proper training from appropriate suppliers.

55. Detonating cord physically resembles safety fuse, but is much different. Detonating cord is a ropelike product with a fabric shell but a high explosive core which must be initiated by a detonator such as a plastic

cap. Once initiated, the detonating cord behaves precisely like an elongate high explosive charge; thus, all charges to which it is connected receive a high explosive shock, and are thus fired nearly simultaneously. Delay connectors are available that incorporate a delay function into a detonating cord firing plan. Detonating cord is used very little underground, and finds application mainly in conjunction with applications of the Nonel system (Richard A. Dick, personal communication).

56. The sources of hazard to an electric initiation system are well defined and well known and in most underground situations they either do not exist or are capable of being controlled. In almost all underground blasting situations, electric initiation systems should be capable of being safely used. It is vital, however, that they be designed and used by well-trained and careful personnel.

57. With initiation systems as well as with explosive products themselves, the best source of information and guidance is likely to be an experienced and reliable explosives supplier.

Cost and performance data for drill and blast tunnels

58. Cost and performance data were collected on many tunnels constructed in the last three decades. These cases include conventionally driven tunnels, roadheader driven tunnels, and TBM-driven tunnels. These cases are summarized in Appendix C under appropriate headings. For the first set of cases, which cover a wide range of tunnel sizes, geological conditions, and geographical areas, average advance rates varied from 10 ft/day for a large tunnel driven through Alpine greywacke, scaly sericite, and chlorite with quartz veins, to 33 ft/day for a large tunnel driven through hard abrasive gneiss. Maximum advance rates ranged up to 750 ft/month. Average advance rates of 50 ft/day are not uncommon in medium size tunnels. Some of these cases were divided into categories based on size and gross geological conditions, where available. The categories were small, medium, and large tunnels, corresponding to tunnels between 9 ft and 13 ft in diameter, tunnels between 14 ft and 18 ft in diameter, and tunnels 19 ft in diameter or larger. Gross geological categories were dry stratified or schistose rock, dry massive rock, dry moderately blocky or seamy rock, dry very blocky and seamy rock, and dry headings in completely crushed or unconsolidated sediments. The effects of groundwater inflows were considered in two categories: wet headings in competent rock and wet headings in crushed rock or unconsolidated sediments.

59. The two most obvious facts that emerge when looking at these case summaries are that: (a) total tunneling costs increase with decreasing rock quality (advance rates go down because heavier, more closely spaced supports must be installed), and (b) when tunnels are driven through water-bearing formations costs jump dramatically, because of the extra precautions that must be taken to insure stability of the face and excavated section. These precautions or requirements add to costs and slow progress. If groundwater inflows are expected, they can be planned for and dealt with effectively. But unexpected high inflows are serious setbacks that require attention before excavation can proceed.

60. The first set of cases summarized in Appendix C were first published by the California State Department of Water Resources in 1959 as part of Appendix C of Bulletin 78. The costs per foot for these tunnels were updated by Mayo, Adair, and Jenny (1968) to reflect 1967 costs. These tunnels are now 25 years old or older so the cost-per-foot data for the different size tunnels and geological conditions are not relevant to present conditions. However, the same trends in costs are probably relevant and emphasize the dramatic cost increases for wet headings in poor rock versus dry competent rock.

61. An examination of five case histories in EM 1110-2-2901 (U. S. Army Corps of Engineers, 1978) of large tunnels (16 to 29 ft in diameter) constructed between 1970 and 1972 show that costs per foot of tunnel ranged from \$500 to \$1555. These costs are uncorrected for inflation. Descriptive characteristics and costs of these 5 and 99 earlier tunnels listed in the EM are listed in Appendix C.

Partial-Face Machine Excavation

62. Improvements in tunneling technology have resulted in introduction of partial-face tunneling machines frequently referred to as roadheaders, digger shields, or boom header machines. They have most of the advantages of full-face tunneling machines, but cost much less and are more adaptable. The shape and size of the excavation is not fixed during design of the machine, in contrast to full-face machines which can only excavate circular tunnels of one size. However, partial-face machines are restricted in terms of the strength of the rock which can be mined.

General description of partial-face machines

63. Figures 6 and 7 show two partial-face tunneling machines. Figure 6 is a shielded roadheader (or boom header) for use in soft ground; Figure 7 is an unshielded roadheader for use in rock. Figures 8 and 9 show the main components of a roadheader. Figure 10 is a schematic of the roadheader excavation method. Digger shields are similar in design and operating principle to roadheaders, with the boom and cutterhead of the roadheader being replaced by an articulated digger arm and bucket. Use of digger shields is restricted to soft ground or very weak rock. Thon (1982) reported that a MEMCO digger shield achieved average advance rates of 113 ft/day on a 26-ft-diam tunnel 2.5 miles long, driven through weak sandstone and siltstone on the Castaic No. 2 Tunnel in California. A roadheader consists of a small rotating cutting head, positioned at the end of a hydraulically operated boom, which in turn is mounted on a crawler frame containing a drive motor and hydraulic equipment. The cutting head is a hemispherical or truncated shape and is equipped with picks or carbide-tip cutting bits in varying number and arrangement. The head is rotated and forced against the tunnel face to chisel the rock under the action of the teeth or bits in a way similar to the action of a hand-held pick.

64. The boom on which the cutting head is attached is controlled by hydraulic rams and can be raised or lowered and moved horizontally from side to side to move the cutter head over the entire face of the tunnel.

65. The crawler frame which supports the roadheader boom carries the power plant as well as a muck-gathering system and conveyor which transports the muck or spoil to the back of the machine. It is then transferred to the muck-hauling system. The machine can travel on crawler treads with cutter forces being resisted by skidding resistance. Higher thrust forces can be applied if hydraulically operated anchor pads are provided on the machine that jack against the tunnel sidewalls and increase resistance. The digger shield's thrust is resisted by jacking the shield against the tunnel walls and usually provides higher resistance to the applied thrust.

Machine types available

66. Because of the limited surface of rock cut by the cutting head during one pass, the cutting power requirements and the overall size and weight of partial face machines are considerably less than those of full-face TBM's. In addition, machine characteristics are relatively independent of the

tunnel size and shape, and with the exception of the cutting head, are independent of the characteristics of the rock to be bored. Therefore, various models of partial-face machines are built in series by various manufacturers.

67. At present, there are over a dozen types of machines on the market and new developments in harder rock capabilities are currently being worked on. The principal manufacturers are AEC, MEMCO, Robbins, and Zokor in the United States; Alpine in Austria; Eickoff, Pamet, Demag, West Failia-Lunen and Paurat in Germany; Dosco, Anderson Mavor, and Thyssen in England; and Atlas COPCO and Ingersol Rand in Sweden. Appendix A lists manufacturer's specifications for some of these machines.

68. Machine power plants range from 30 to 800 hp, with most in the 70 to 200 hp range. Boom lengths can be very short (about 3 ft), for the powerful stiff machines used in hard rock to boom lengths of 10 ft or so for the more versatile machines.

69. The strength of rock which can be successfully mined by partial-face machines is limited by the type of cutting tools mounted on the cutting head and by the maximum thrust and torque which can be developed on the cutting head. The maximum thrust and torque on the cutting head are both necessarily limited by the fact that the head is mounted on a boom and that the relatively light machine is not anchored. Although anchored machines have shown promise, at present the thrust available in most machines is about 6,000 to 12,000 lb, but can be as high as 25,000 lb for very large machines. As a consequence, partial-face machines cannot mine through rocks with a compressive strength in excess of about 20,000 psi. Excavation rates decrease rapidly as rock strengths approach this limit. Handewith (1983) indicates that the upper-bound strengths for economic production decrease as the abrasiveness of the rock increases. He suggests these limits are 18,000 to 22,000 psi for nonabrasive sedimentary rocks, and 8,000 to 10,000 psi for very abrasive rocks (sandstone). He defined abrasivity as the percent by volume of minerals with a Moh's hardness greater than 5 1/2 (cannot be scratched with a knife).

70. Adaptability of the machine to varying local rock conditions is obtained simply by selecting an appropriate cutting head. In very soft rocks, the cutting heads are fitted with a limited number (20 to 30) of teeth with tungsten carbide steel tips or the digger shield may be used. In harder rocks, the number of cutters is increased and their type is changed from teeth to conical carbide steel bits, which can rotate in their housing for even wear

and resulting longer life. Changing the worn-out cutting tools is an easy operation due to the accessibility of the cutting head and the small dimension of the cutters.

Partial-face excavation method

71. The cutting of the rock face is carried out in passes of about 1 to 2 ft corresponding to the dimension of the cutting head. To cut the full tunnel face, the cutting head is moved in horizontal passes, generally starting from the invert of the tunnel to ease the excavation process by undercutting the rock. If layers of harder rock are encountered, they can first be exposed by excavation of the softer surrounding rock to make their disintegration easier by adding flexural forces to the normal cutting action. Any shape of tunnel can be excavated, provided it is within reach of the boom; horseshoe-shaped tunnels can be readily formed. Roadheaders can be mounted within a tunnel shield (Figure 6) to make them suitable for use in widely varying ground conditions from moderate strength rock to crushed rocks or mixed face. Recent shield designs for use in mines have made provision for the shield to be self-advancing, by using a system of breasted face boards actuated by hydraulic support props. The advantages in adverse ground are the ability to carry out ground treatment ahead of the face and to deal with large boulders. Boulder clay has always presented a problem for fullface soft ground tunnel boring machines. The boulders either jam the machinery system or are pushed by the machine to one side of the tunnel line. This was a particular problem with the bentonite slurry machine at Warrington, U. K.* For this reason, European contractors favor partial-face shield machines for difficult ground.

Dust control

72. The problem of dust control is of major importance with partial-face machines since the operator must see the face during excavation to guide the cutting head and avoid "tight spots" or overbreak. Dust is generally controlled by two simultaneous means: a water-spraying system is fitted to the end of the boom or in the cutting head to wet the rock dust directly at the cutting face and produce at least a partial precipitation; in addition, suction-type ventilation ducts are fitted to the boom or to the front end of the machine to remove any remaining dust.

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* Personal communication, H. J. Hignett, June 1982.

Performance data

73. A few cases of roadheader performances are summarized in Appendix C.

74. Average rates of advance for partial-face machines are generally accepted to be slightly in excess of those for drill and blast methods but, of course, much lower than those of full-face TBM's. McFeat-Smith and Fowell (1979) report that roadheaders can achieve up to 40 percent greater advance rates than drill and blast methods. They report average advance rates per 100 hr workweek at 150 ft for drill and blast and 215 ft for roadheader excavation for the same tunnel cross section. Excavation of 100 yd^3 per 8-hr shift is considered a high average. Progress can be much slower in hard rocks.

75. Rates of excavation ranging from 11 to 60.5 m^3 per hour were reported by McFeat-Smith and Fowell (1979). The lower reported rate corresponded to a light machine used in sandstone and mudstone. The upper rate was for a heavy machine in mudstone. Utilization varied from 39 percent to 56 percent. Of the unproductive time, support installation accounted for between 12 and 34 percent, mucking problems accounted for 3 to 15 percent of lost time, and other stoppages accounted for the rest. Pond (1983) reported average advance rates of 11 ft/day for a heavy (45 ton) Paurat E-169 roadheader used to sink a 14 deg decline in Kentucky through shale and sandstone with strengths ranging from 4100 to 10,500 psi. Support installation was reported to be the primary factor limiting advance rates in the weaker strata.

Advantages and limitations

76. In general, rates of advance are as dependent on the ground conditions and support requirements as they are on the actual cutting ability of the partial face machine. The rock surrounding the tunnel opening tends to remain relatively undisturbed and, therefore, retains most of its self-supporting capacity. Consequently, support requirements for tunnels excavated by partial-face machines are very similar to those associated with full-face TBM's.

77. The problems of vibrations and their influence on the local environment are also minimized. Geometric constraints of partial-face machines are minimal as compared to full-face machines. The machines can excavate any size and shape of tunnel within the limits imposed by machine size. Also, partial-face machines are capable of excavating practically any curve radius, a definite advantage over TBM excavation in some cases.

78. Limitations related to rock quality are not as stringent for partial-face machines as for TBM's. In particular, because the tunnel roof and walls are accessible at all times immediately behind the face, support systems, if required, can be easily installed so that partial-face machines can work in rocks and soils of lesser quality than full-face TBM's. Groundwater inflows are handled by grouting ahead of the face or the use of compressed air. Also, variability in rock conditions is not a serious problem unless zones of hard rock are encountered.

79. Since partial-face machines are smaller in size and horsepower rating than TBM's and are built in series, their cost is much lower than that of TBM's and is only slightly higher than that of drill jumbos. This lower cost, associated with the fact that the same machine can be used without major modifications in various sizes and shapes of tunnels, minimizes depreciation of capital costs solely on one contract.

80. The most significant disadvantage of partial-face machines is related to the strength of rock which can be mined. Examples of partial-face machine performances tabulated below illustrate the dramatic decrease in productivity that can be expected as material hardness increases. As stated previously, partial-face machines cannot bore rocks with a compressive strength in excess of about 20,000 psi and their productivity is markedly reduced even if occasional layers of such hard rocks are encountered. Where the use of roadheaders is proposed, it is essential that geotechnical investigations be oriented toward the identification of such hard rock layers. A further disadvantage, as compared to TBM's, is the slower rate of advance of partial-face machines. However, this disadvantage, in some cases, may be offset by the lower capital costs.

81. Examples of the performance of a partial-face machine are tabulated on the next page.

Material	Hardness kg/cm^2	Machine excavation rate* m^3/hr
Clay	50	55
Shale	650	21
Shale/marl/clay	400	20
Shale/marl/sandstone	500	15
Mudstone/siltstone	500	19
Siltstone/sandstone	900	12
Gypsum	630	13
Iron ore (32 percent Fe)	500	15

* The machine excavation rate is the output from the machine in one hour of continuous excavation. Normal overall averages are 50-60 percent of the machine excavation rate.

TBM Excavation

82. The use of full-face tunneling machines dates back to 1882, with Beaumont's design for the Channel Tunnel Machine. However, only in the last three decades has full industrial development of TBM's taken place.

83. Over the past 10 years, the use of TBM's has become widespread. With this increasing use, major improvements have been achieved in the design and performance of machines and cutters. Further, the overall reliability of the various components of the TBM has been increased to reduce downtime which was a major problem. As a result, TBM's can now be used in rocks with compressive strengths up to 30,000 psi or higher, and are extremely competitive when compared with other methods in soft rocks with compressive strengths of less than 20,000 psi. Advance rates in suitable ground conditions can be over three times the advance rate that can be achieved by conventional drill and blasting. All TBM's are designed for specific projects and specific driving conditions. Two basic philosophies of design exist for TBM's, namely "soft ground" machines and "hard rock" machines. For soft ground machines the design philosophy is based on ground support considerations; cutting presents few problems. For hard rock machines, design philosophy is based on cutting; ground support is a secondary consideration. In the latter case insufficient attention to primary support has sometimes caused problems.

General description of TBM's

84. Figures 11, 12, and 13 show modern full-face tunnel boring machines. Figure 11 presents a soft-ground TBM and Figure 12 shows a shielded-rock TBM.

This figure shows a feature of the face that is discussed in more detail later in this section; i.e., grill bars added to prevent loose rock blocks from sliding in against the face. Figure 13 is a rock TBM for use at greater depths, where a shielded design can result in problems caused by friction between the rock and shield and the lack of provisions for immediate installation of supports.

85. The main components of a soft-ground TBM are shown in Figure 14. These machines are also known as drum diggers or shield machines. The cutting head is mounted on a drum which revolves inside the outer shield. With the rotary drive system mounted on the outer shield, the central portion is left relatively open, thus permitting access to the face, for face stabilization, if required, and ease of cutter change. The muck is picked up by the cutter head and transferred via the discharge hopper to the primary conveyor. The shield is propelled forward by thrust rams located at the rear of the shield and react either against a specially built reaction ring or concrete segmental linings. Figure 15 is a sketch of concrete segmental lining rings. When concrete segment linings are used, a segment erection facility is provided inside the shield at the rear of the machine.

86. Major components of two hard-rock machines are depicted in Figures 16 and 17. These machines consist of a wheel cutter head fitted with roller discs to cut or spall the rock. The wheel is slightly smaller than the bore of the tunnel and is equipped with gauge cutters on the periphery of the wheel to produce the designed bore. The wheel may consist of reinforced spokes or may be a solid disc with slots to allow the muck to pass through. The wheel is rotated at speeds which vary between 4 and 10 rpm depending on the diameter. The speed is controlled by means of electrical or hydraulic disc motors. The wheel is forced against the tunnel face by hydraulic jacks which apply a thrust varying between 200,000 and 5,000,000 lb, depending on the strength of the rock and tunnel diameter. The wheel is attached at the end of a tube called the "backbone" which contains the electrical controls, the hydraulic pump, and sometimes the drive motors. The backbone is enclosed within a structural steel framework. This framework is equipped with two or four hydraulic thrust jacks and contoured pads or shoes that can be jacked against the tunnel walls. These gripper pads control grade and alignment of the machine and resist the torque and thrust of the cutting head. As excavation proceeds, the rock cuttings fall through the slots in the cutting head

and are picked up in buckets attached around the rim of the wheel. The muck is discharged onto a conveyor belt incorporated in the machine. The conveyor moves the muck to the back end of the TBM via a gantry conveyor where it is discharged into cars or other muck handling equipment. To advance the machine, the cutter head and backbone can be jacked forward at a constant rate for a stroke of up to 6 ft.

87. Many types of "hard rock" full-face TBM's are available; the principal manufacturers are Robbins in the United States; Priestley in the United Kingdom; Demag, and Wirth in West Germany; and Atlas Copco-Jarva in Sweden. There are other manufacturers who have built a few TBM's. Robbins has built more TBM's than all other manufacturers combined. However, this does not imply that there is nothing to be learned from other manufacturers.

88. TBM manufacturers design their machines specifically for the expected geological conditions. In many cases, prediction of the geological conditions has been incorrect. The results of poor site characterization and lack of attention to contingency plans to deal with changed conditions are delays, cost escalation, and, quite often, claims and litigation. In general, there are few, if any, ground conditions that a TBM cannot be designed to handle. However, TBM's are not a universal answer for any tunnel excavation. Many factors must be evaluated to determine whether a tunnel should be driven by machine or drill and blast.

Advantages and disadvantages

89. A negative feature of the drill and blast method is the delay caused by cyclic operation. In contrast, TBM's operate on an almost continuous basis; the only unproductive time in the cycle is that required to advance the reaction frame at the end of each "shove." The continuous advance results in higher hourly rates of advance and in an optimum use of ancillary tunneling equipment such as muck handling and ventilation systems. However, this theoretical continuous operation of TBM's is never achieved over long periods of time because of mechanical breakdowns, scheduled maintenance, and other interruptions. Rate of advance of the tunneling operation is controlled by its slowest or least reliable component. In early stages of development, the machine itself was the controlling (slowest) component, but now, TBM excavation rates have increased to the point where other operations usually control the overall advance rate. Under good rock conditions or in small tunnels the controlling element may be the muck handling system. Under poor rock

conditions, support installation or ground stabilization may be the bottleneck, preventing full utilization of the TBM's capabilities.

90. Tunnel boring machines present important advantages in terms of the quality of the tunnel opening produced. In good rock, all TBM's produce a smooth bore. Consequently, overbreak is practically eliminated, with a resulting reduction in the quantities of muck to be handled and of concrete in the lining. A further benefit resulting from the smooth bore and from the elimination of blasting vibration, is that loosening of the rock in the walls and roof of the tunnel is considerably reduced so that the rock requires less support. Support requirements for machine-excavated tunnels are often significantly less than for drilled and blasted tunnels, a fact that has not escaped owners or contractors. Besides the reduction in quantities of support, time is also saved in installation of supports.

91. A further advantage is that because of the absence of blast-induced vibrations TBM operations are not as damaging to the local environment. In urban areas, this aspect is important since special precautions are not necessary to minimize blast-induced damages to nearby structures.

92. Tunnel boring machines present some important disadvantages which may reduce their potential use under some conditions. Full-face TBM's are able to produce only circular tunnel sections. Such a cross section is ideal for water or sewage tunnels, but transportation systems require a flat invert to support the track or road bed. For such tunnels a horseshoe shape is sometimes preferred. However, a circular shape is better from the point of view of stability of the tunnel opening and resulting support requirements.

93. A given TBM can usually bore only one size of tunnel since the dimension of the bore is determined by the diameter of the cutting head and the position of the gauge cutters on the head. The diameter bored can be varied by about 1 ft on some machines, but in general, a new machine has to be manufactured for each new tunnel. Standardization of tunnel sizes on a large scale has been suggested as a partial solution for reducing the lead time for manufacture and delivery of TBM's.

94. Another geometric constraint in the use of TBM's is related to the minimum radius of curvature. The sharpest curve which can be negotiated by a TBM depends on the shape of the machine, on the diameter of the structure behind the cutting head, on the possible range of adjustment on the hydraulic arms, and on the length of the backbone and the structural frame. Five hundred

feet might be considered a desirable minimum radius of curvature. The minimum curve radius that a TBM can negotiate is about 10 to 15 diameters for an unshielded machine and about 20 to 30 diameters for a shielded machine.

95. TBM's can be used to excavate sloping tunnels with maximum grades up to 15 deg downgrade and to 45 deg upgrade (Nishida et al., 1982, Thon, 1982, and Sudgen, n.d.). Uphill excavation is usually preferred over downhill because muck is then hauled downhill, reducing power requirements, and water inflows are much more easily handled. Indeed Thon (1982) reported that a 10-ft tunnel, bored at a 33-deg uphill incline through granite on the Emgosson project in Switzerland, required no muck handling system. The muck was simply washed out of the tunnel. A later tunnel on this same project was bored at 42 deg and used the same muck handling method. Special attention must be given to the lubrication system and seals when a TBM is to be used to drive either uphill or downhill.

96. Limitations to TBM use are related to the ground condition or quality of rock mass and other factors, including tunnel length. The ability of a TBM to cope adequately with variable ground conditions depends on its design. The more versatile the machine is and the more features incorporated on the machine, the more expensive the machine is.

Factors that affect TBM design

97. The most important factor influencing machine design is that of geological variation and its prediction. Most cases of TBM failure have been the result of incomplete information about the tunneling environment rather than mechanical problems with the machine itself. After careful study of the geological conditions, the machine should be designed for the worst conditions expected, which in some cases, may preclude use of a TBM. The following variable rock characteristics influence the design of a TBM and may, in some cases, preclude use of a TBM:

a. Compressive strength of rock.
b. Rock abrasivity.
c. Rock mineralogy.
d. Rock mass stability and deformation properties.
e. Induced stresses in rock masses.
f. Groundwater regime.
g. Stand-up time of tunnel opening.
h. Presence of gas.

98. In general, rock unconfined compressive strength and estimated stand-up time of the tunnel opening control the philosophy of design. Figure 18 relates stand-up time to unsupported span of tunnels. It is important not to confuse stand-up time of rock opening with final support requirements. Final support requirements need not influence TBM design. The prime objective of a TBM is to excavate the tunnel opening on a nearly continuous basis. This objective cannot be met unless provisions have been made to install primary supports and remove the cuttings as they are produced. Too many cases exist where consideration of final lining design and placement has overridden the prime requirements of a TBM, to the detriment of the overall project.

TBM performance considerations

99. The rate of advance of a TBM can be controlled by many factors. One important consideration is the crew using the machine. Contracts should be written to provide incentive and motivation to the crew, with realistic financial targets for the client. There is generally a learning period, even for experienced crews at the start of a project before full utilization of the TBM is achieved. This period is usually 3-4 weeks.

100. Other important factors that influence TBM excavation are cutter selection, cutter arrangement, head speed, thrust available, primary and secondary mucking, primary support erection, groundwater control, ground control, and alignment and grade control.

101. Cutter selection. The general types of cutters available are shown in Figure 19. A description of each follows:

a. Drag picks. Tools which are commonly of simple chisel form (although more complex shapes are available) and which are assembled in an array on the peripheral surface of a rotating drum or face plate of a soft ground TBM. They are also sometimes used for trepanning, planing, or milling a rock face. This tool is widely used in the coal mining industry. It is generally recognized that the upper limit for using drag picks is 10-12,000 psi unconfined compressive strength, although some success has been reported in rock of higher strengths. Figures 19a and 20 show drag pick cutters.

b. Disc cutters. A solid disc with a pointed circumferential edge. The disc operates as a free rolling wheel. High applied thrust forces the disc into the rock in much the same way as a heavily loaded wheel rolling over yielding ground. Figures 19b and 21 show the disc in its simplest form, but it can take on a multiple-edged or asymmetric configuration. TBM's equipped with discs have very few cutting problems in rock up to an unconfined compressive strength of 25,000 psi or so. For rocks with higher strengths, penetration rates that can be achieved are lower and the cutter costs are higher. Drill and blast methods are usually favored for driving hard rock tunnels. However, recent improvements in disc bearing design and development of stiffer machines are increasing the maximum rock strength for practical TBM excavation toward 35,000 psi.

c. Roller cutters. Figure 19c shows a roller or star wheel cutter, similar in concept and design to the disc cutter. However, its circumference is equipped with teeth, having an appearance very similar to that of a simple gear wheel. As each tooth engages the rock during free rotation of the wheel, a rock fragment is chipped away. This tool is extensively used in the oil industry for drilling large-diameter boreholes to great depth. High rotational speeds required for effective operation and the requirement for periodic flushing between cutting segments effectively preclude their use on TBM's.

d. Carbide button cutters. Figure 19d shows carbide button cutters mounted on a raise drill cutterhead. This grinding bit usually takes the form of a free rolling cylinder or cone frustum, the surface of which is studded with tungsten carbide buttons. It is operated in a fashion similar to the disc and roller cutter. A high thrust force is applied to the rock surface, and torque is applied to the cutter head to cause rock degradation by grinding and pulverization. This type of tool is suitable for cutting rocks with unconfined compressive strengths in the range of 25,000-30,000 psi. This type of tool has been used for gauge cutting, where several cutters can be placed on the same path, giving several full circumferential cuts per revolution.

102. Cutter arrangement. The most suitable shape and size of rock-cutting tools for use on a range of rocks can best be determined from tests in the laboratory using an instrumented shaping machine or similar system. The cutter is mounted on a triaxial dynamometer on the machine head and the rock under investigation is fixed to the machine bed while tests are carried out using a range of tool shapes and sizes.

103. By monitoring the forces and the amount of rock excavated, the tool shape with minimum cutting energy requirement per unit quantity excavated, within the range of depths of cut under consideration, can be determined, as well as an optimum depth of cut and spacing between adjacent cutters. A cutting tool breaks out more rock than the volume swept by its projected area. Additional breakage occurs at the sides of the cut and is termed "side-break." Correctly spaced cutters maximize this "side-break" effect.

104. Within limits, the spacing of tools (S) to achieve maximum interaction between adjacent cuts is a function of the depth of cut (D) so that the ratio of tool spacing to depth of cut is the important consideration when deciding on arrangements of cutting tools. The spacing of cutters is usually fixed on the machine, so changes in the S/D ratio are obtained by altering the depth of cut. The depth of cut (D), the rate of advance of the machine (V), the rotational speed of the cutter head (ω), and the number of cuts on the same path per revolution (C) are related by the equation:

$$V = D\omega C \quad \text{or} \quad D = V/\omega C$$

105. Hignett and O'Reilly (1977) have examined interactive effect of tool placement and design procedure for placement of cutting tools.

106. Head speed. The cutting head of a TBM excavates the tunnel and gathers and loads the muck onto the primary conveyor. Muck dumping occurs at the highest point of the rotation by gravity. The rotational speed of the cutting head is therefore limited because the centrifugal force holding the muck in the bucket must be less than the gravity force. Otherwise, the muck will not dump onto the primary conveyor. Typical TBM head speeds are 4-6 rpm.

107. Thrust. Thrust controls the penetration of the cutter into the rock. Typical thrust forces required on one disc for an acceptable penetration range from 12,000 to 50,000 lb. The total thrust required is thrust required per disc times number of discs. The thrust required to move the machine forward must be added to this value.

108. Total thrust can be over 500 tons and must be resisted by pressure pads on the tunnel walls. Total resistance that can be developed by these pressure pads sometimes limits the total thrust that can be applied to the face.

109. Mucking. The swell or bulking factor of muck is usually between 1.2 and 1.4. The muck volume that must be removed over a given period may be calculated from the tunnel diameter, maximum advance rate expected and the bulking factor. TBM excavation rates have steadily increased in soft competent rocks and are now at the point where muck removal through the machine and out of the tunnel can be a major constraint on advance rates.

110. Primary support erection. One of the major factors influencing overall TBM performance is the rock mass character. Very few tunnels can be

driven without any support. Although most of a tunnel's length may need no more than relatively minor stabilization measures, part of the alignment may require extensive measures. The TBM and its backup systems must be designed not only for the average conditions, but also for the most difficult condition.

111. The limit of technical feasibility of TBM excavation is controlled by the rock mass stability and ground deformation. Stability can be assessed in terms of stand-up time, the elapsed time after excavation that an unsupported tunnel face will remain stable (i.e., no major fallouts or excessive ground loosening). The most important factors influencing stand-up time are:

- a. Time-dependent strength - deformation characteristics of the rock mass.
- b. In situ state of stress.
- c. Groundwater regime.
- d. Size and shape of opening.
- e. Method and rate of excavation.
- f. Method and rate of support installation.

112. For the evaluation of opening stability, it is important to note that interaction of the TBM with the tunnel environment strongly influences the heading stand-up time.

113. Ordinary hard rock TBM's cannot operate in conditions where the stand-up time is very short. Figure 18 gives an empirical relationship between stand-up time and unsupported span for five different categories of rock masses after Bieniawski (1979). A collapsed heading will jam the machine cutter head making it impossible to operate. Ground with intermediate stand-up time can be effectively controlled, provided the machine has provisions for the rapid installation of support and/or reinforcement near the face. Supports can be installed quickly near the face only if provisions have been made for access to the region immediately behind the TBM cutterhead. Stability of the opening can be improved sometimes through the use of grouting or other methods of ground prereinforcement. A TBM designed without provisions for installation of primary support close to the face invites problems if poor ground conditions are encountered. In the worst cases, TBM's have been abandoned after being immobilized by large roof falls or intense squeezing conditions.

114. <u>Groundwater control.</u> When encountered, large groundwater inflows must be controlled by grouting before excavation can proceed. Actual flooding of the tunnel is possible, but if contingency plans have been made for pumping

and grouting, inflows can normally be controlled before inundation. Grouting methods and other groundwater control measures are discussed in Part VI.

115. Ground control. The difficulty of predicting the exact nature of the ground ahead of the TBM has in many cases caused difficulty in TBM operation. The ability to grout ahead, drive in fore poles or back the machine from the face and blast, are all factors to be considered in machine design. Methods for ground control and support are discussed in detail in Part VI.

116. Alignment and grade control. If a TBM drops below grade, it is very difficult to maneuver back on line. It is necessary to stop the drive for remedial work. After backing the machine off the face a steel and/or concrete ramp can be constructed in the invert. The machine cutter head is then simply skidded up the ramp to the proper elevation. Of course, it is first necessary to overexcavate the crown to make room for the machine. If this is carried out by blasting there is always the possibility of damage. Attempts to jack up TBM's after they went off line have sometimes been unsuccessful, and subsequent remedial work was required.

117. Temporary problems with gripper pad slip or bearing failure are commonly remedied by increasing the bearing area with timber or concrete packing. In extreme conditions a concrete buttress or wall plate can be formed along the tunnel side wall. Under certain conditions it is also possible to thrust off of ground supports at the rear of the machine. Another solution includes reducing the forward thrust required to excavate by constructing a pilot hole ahead of the tunnel face. High thrust loads and gripper pad slippage contribute to steering problems.

Machine tunneling under adverse and variable ground conditions

118. TBM's can be designed for nearly any type of uniform soil or rock, and as long as the tunnel alignment stays within the type of material the machine was designed for, good progress can usually be expected. However, geological conditions are seldom constant over long distances. Unexpected abrupt changes from good to poor rock conditions slow progress until the tunnel passes through the bad ground zone. In worst cases, progress may be stopped completely until adequate control measures can be devised. Such zones of bad ground in otherwise competent rock seldom persist over long distances but these segments can account for much lost time and increased costs.

119. The most troublesome conditions are high inflows, squeezing or swelling ground, and shear or fault zones of blocky crushed rock. Even well-planned and executed geotechnical investigations often fail to find evidence of these adverse conditions prior to construction. Large inflows can usually be handled by grouting or pumping, if these measures have been planned and the necessary equipment, materials, and personnel are on site. Inflows large enough to cause flooding usually give very little advance warning so the tunnel boss must be always alert to this danger and be ready to quickly evacuate the tunnel. If the tunnel floods, much time will be lost in pumping and repairing damage before excavation can proceed.

120. Squeezing or swelling ground can cause the machine to become stuck. The rock or soil, upon excavation, has an unloaded or free surface. Unequal stress distribution in the mass surrounding the tunnel and exposure to air and moisture results in convergence of the tunnel walls. Swelling pressures on the tunneling machine's shield can be tremendous. Thon (1982) reported a case on the BART system where the TBM became stuck in serpentine during a 3-day holiday shutdown. The machine was finally pulled free, only to have the roof collapse. Five weeks were required to hand mine through this 20-ft section. When the second of the twin tunnels passed through this same zone, progress was maintained continuously and no problems occurred. This case emphasizes the need to tunnel through such zones as rapidly as the machine can be pushed and support can be installed. Support should be placed as close to the face as possible. Squeezing or swelling conditions might be expected in certain rock types, especially at great depths or in near-surface zones of variable high stress. Certain shales and serpentine are well known for their swelling potential.

121. Seamy, shattered, or crushed rock is unstable until supported. Stand-up time is very short. Blocks and debris may start to fall out immediately and get progressively worse if support is not applied quickly. Such conditions impede the progress of any excavation scheme and are very dangerous. TBM's are especially vulnerable to unstable conditions because of the long unsupported span between the face and tail shield where supports are normally installed. Roof falls can bury a TBM for weeks until the debris can be cleaned away and the cavity supported above the machine.

122. Face instability results in large blocks sliding out against the TBM cutterhead. The blocks jam in the muck buckets or against the cutterbit

mounting brackets and must be broken up by hand and removed. Otherwise, the blocks can gouge material from the face or circumference, causing further problems. The machine must be stopped and backed up to remove the blocks and repair damages if required. Figure 12 shows one manufacturer's method for controlling face instability by the use of concentric ring bars mounted on the face. Figure 13 shows another variation to accomplish the same objective. On the Southeastern Trunk sewer tunnel completed in the early 1970's in Melbourne, Australia (Thon, 1982), intensively shattered Siberian sandstone and mudstone slowed progress (advance rates averaged 4 ft per shift during the first six months) of a Robbins TBM until major field modifications were made to the cutterhead and shield. The major problems with the original machine design under these conditions were (Thon, 1982):

> a. "The horizontal distance from the front edge of the shield to the central cutter was 3 ft, leaving the rock virtually unsupported in this region.
>
> b. The cutters dragged blocky material across the working face, disturbing unstable ground ahead of the machine.
>
> c. The buckets became jammed either with clay or with large blocks of rock, which then gouged out more rock and caused extensive overbreak.
>
> d. Instead of cutting the rock in loose ground, cutters and buckets frequently stuck and stalled the machine.
>
> e. Poor access to the front of the machine made it impossible to inspect or change the cutters in bad ground. During cutter maintenance in unstable ground, the rock ahead of the machine frequently caved in and then had to be stabilized by hand-mining operations around the head of the machine.
>
> f. The front side gripper pads tended to push into soft ground as the machine moved forward, putting it off-line and damaging the ground.
>
> g. The disc cutters required a high thrust for proper operation. In faulted ground, they tended to skid without rolling, causing flat edges to develop.
>
> h. Ground failure tended to occur along the top of the shield, partly because the shields subsided when adjustments were made to the hydraulically actuated support system and partly because of contact between the shields and the surface of the bored tunnel."

123. Extensive redesign of the machine was completed after about six months of dismal performance, and the machine was removed from service to carry out the required modifications (Thon, 1982):

a. "A new shield was placed over the cutting head. The shield segments were mounted on spring-loaded arms, giving them greater flexibility. The radius of the shield segments was only 1/2 in. less than the bored radius of the tunnel to support the roof effectively. In addition, the shield was fitted with a series of trailing fingers made from steel plate that would allow forepoling operations to take place ahead of the machine in bad ground.

b. The cutting head was modified. The tricone center cutters were replaced with a group of eight drag cutters with tungsten-carbide tips, clamped together as a unit. Drag cutters were used as face cutters, mounted in front of the disc cutters, so that the drag cutters would operate in soft material; if the drag cutters wore too rapidly, the disc cutters would operate. Finally, drag cutters were used as the gauge cutters.

c. The rotational speed of the cutting head was reduced, which lessened the problem of boulders being dragged across the working face and also helped considerably to increase the life of the drag cutters.

d. Various modifications were made to the buckets to obtain an improved flow of material into and through them to reduce the number of blockages.

e. The surface area of the side gripper pads was increased. This reduced the bearing pressure against the tunnel walls and eliminated the tendency to dig into the softer ground.

f. Other modifications included an overload cutout and absorption brake to reduce damage when the cutting head jammed in soft ground. The main beam was extended 10 ft and included a 5-ft long hole to provide access for men and materials to the working face."

124. When these modifications had been completed, the machine was put back on the job and its advance rate increased by a factor of four to five resulting in 16-20 ft per shift.

125. Problems similar to those experienced on the Melbourne sewer tunnel were encountered on the recently completed Buckskin Mountains Tunnel in Arizona. This 22-ft-diam U. S. Bureau of Reclamation tunnel was driven 35,000 ft through complex volcanic rocks with unconfined compressive (UC) strengths up to 43,000 psi. The contractor had initially been concerned with the rock hardness but extensive, open, near vertical fractures in the rock proved to be a far more serious problem. The 23.5-ft-diam Robbins TBM was equipped with telescoping shields and 58 15-1/2-in.-diam single disc cutters. The cutters protruded about 16 in. from the face of the cutterhead. After boring the first 1400 ft of tunnel, severe problems were experienced (Parkinson, 1977, Engineering News Record, July 1977, and Shea, 1981). Massive blocks

"some as large as desks" fell from the roof and dented the roof shield. In addition the 16-in. space between the tunnel face and the cutterhead allowed blocks as large as 4 ft to slide out against the cutterhead and jam in the muck buckets and stall the machine. The contractor decided to modify the TBM to deal with these adverse conditions. Modifications were carried out in the tunnel and required about 6 months. First, the TBM was backed up and working space around and above the TBM was created by hand mining. A false face was welded onto the cutterhead reducing the gap between the tunnel face and cutterhead face from 16 in. to 4 in. In addition, 24-in.-diam by 11-in. deep by 1-in. thick pipe sections were welded around the cutter bearing housings and were flush with the false face. These modifications greatly improved face stability.

126. The roof shield was reinforced with steel rib stiffeners to resist damage from falling blocks.

127. After these modifications the TBM achieved much better progress (75 ft/ day was reported by Parkinson (1977) and 335 ft/week was reported in California Builder and Engineer (September 23, 1977) for a 5-day, 24-hr operation).

128. These results were not ignored by the manufacturer. Robbins has since incorporated most of these features into a new line of tunneling machines especially intended for use in variable ground. These machines can cut through soft ground and rock.

129. The SILA Project, a hydroelectric power tunnel in southern Italy, was driven by this type of machine, a 14.5-ft Robbins TBM (Thon, 1982). This TBM was equipped with a spoke-type cutterhead and full circumference, double telescoping shields. Precast concrete segments, installed in the tail shield, provided support for the highly weathered and unstable granite. The cutterhead was designed to allow easy access to the face for cutter replacement or hand mining operations in very bad ground. Circumferential bars were welded over the muck bucket openings to limit the size of blocks that could enter the bucket. This machine was reported to have encountered unconsolidated and crushed material so unstable that the face ran in against the cutterhead. Boulders larger than 2 yd^3 slid from the face into the machine with such force that the machine was knocked backward. The boulders jammed the cutterhead and had to be removed by hand. Field modifications were required to the TBM to get through this zone. The contractor, S.E.L.I. Corporation, Rome, Italy,

modified the cutterhead by welding concentric steel plates over the cutterhead. This shield rotated with the cutterhead and reduced the unsupported distance between the face and the shield from about 16 in. to 4 to 5 in. In unstable ground, rock blocks could only move a few inches before being supported by the face plates. The close spacing of the face plates prevented muck larger than about 8 in. from entering the buckets. This field modification was so successful that the machine was able to excavate through this bad zone that would have been impossible otherwise. Such rock would normally require forepoling and closely spaced steel ribs and shotcrete or breast boarding.

Capital costs of TBM's

130. TBM's are complex pieces of equipment and their capital cost is very high. A typical 16-ft-diam machine might cost more than $4,000,000, or several times the cost of a drill jumbo for a tunnel of equivalent size. Clark, Ozdemir, and Wang's (1980) report estimated costs for Robbins conceptual designs for egress TBM's at $3.6 million for a 15-ft-diam TBM and $4.8 million for a 19-ft-diam "hollow" machine. These figures include a 50 percent contingency add-on to "normal" costs. The 12.5-ft-diam Robbins TBM used on the Thompson-Yarra Tunnel in Melbourne, Australia, cost about $3.3 million. The 23.5-ft-diam Robbins TBM used on the Buckskins Mountain Tunnel cost about $2.5 million in 1975 (Construction Methods and Equipment, Aug 1977).

131. Further, since a TBM is normally custom-built for a specific project, the contractor must usually assume a 100 percent write-off of the cost of the machine when bidding a project. Thus, for a TBM to be competitive in cost with drill and blast excavation methods, the tunnel must be long enough for the faster, more efficient TBM operation to offset the relatively higher capital cost. As a rough guide, the minimum economical length of a TBM driven tunnel is about 1 mile.

Mobilization

132. Manufacture of a custom-built TBM generally requires from 9 to 12 months between the placement of the order and delivery on site. Because a contractor cannot place the order before the contract is signed, this period constitutes the mobilization time. This time is not totally lost because of preparations that must be made before the TBM can start work (access roads and utilities may have to be provided, shafts must be excavated, and the first few hundred feet along the tunnel length must be excavated by drill and blast).

However, the delivery time of a TBM generally results in longer mobilization times than the drill and blast method. Therefore, to achieve maximum advantage from the use of tunnel boring machines, it is essential that major projects be conceived in terms of long contractual tunnel lengths and realistic mobilization periods.

Cost and performance data

133. It is difficult to make meaningful generalizations about costs and advance rates in tunnels. Costs and advance rates vary widely for many different reasons, as discussed previously. However, a few factors emerge as very important to success or failure. Changed conditions are probably the most common reason for cost increases in tunnel work. Unexpected groundwater inflows and poor rock conditions can slow or halt progress and drive costs up. Squeezing rock or blocky or crushed rock can shut a job down if provisions have not been made to install supports immediately behind the face. On the other hand, relatively soft competent rock makes for ideal TBM tunneling conditions. Under these conditions average advance rates of 100 ft/day and higher have been reached, but 50-70 ft/day average advance rates are more common. A Robbins TBM achieved record maximum advance rates of 419 ft in one day and 1905 ft in one week on the 10-ft-diam Oso Tunnel in Colorado. This tunnel was driven through soft shale with a maximum compressive strength of 500 psi. The average rate of advance was about 133 ft/day, excluding time lost in bad ground (Thon, 1982).

134. Soft-ground drum diggers or TBM's have been used for many projects and have achieved sustained advance rates of over 300 ft/week. Their limitations are ground depth and competence of rock. High ground stresses can cause rapid dilation of the tunnel opening and can cause the shield to stick. Excavation of rock above 10,000- to 12,000-psi unconfined compressive strength requires a more robust machine design because of power and thrust requirements. Some TBM's have been designed to incorporate both the principles of soft-ground and hard-rock machines where variable ground conditions are expected.

135. Tabulated data on sixteen TBM tunnels driven between 1969 and 1975 by the Metropolitan Sanitary District of Greater Chicago (MSDGC) are summarized in Appendix C. For three small tunnels between 6 ft, 6 in. and 9 ft diam, average advance rates ranged from 19 to 72 ft/day. The maximum rate achieved on two of these tunnels was 153 ft/day. For three medium tunnels between 14 and 18 ft diam, daily average advance rates ranged from 38-126 ft.

The maximum advance rate achieved on the 14-ft tunnel was 265 ft/day. For ten large tunnels between 21 and 35 ft diam, average advance rates ranged from 48-76 ft/day. Maximum daily rates on these tunnels ranged from 100-188 ft/day. Most of these tunnels were driven through hard dolomitic limestone of good quality. Of interest are the data shown in this table on man-hours labor required per cubic yard excavated (mh/yd^3). For small tunnels man-hours per cubic yard range from 2.2-3.4. For medium tunnels, between 0.4 and 1.8 mh/yd^3 were required. Large tunnels required 0.2-0.6 mh/yd^3 excavated. The trend is apparent in these data. Excavation of large tunnels is simply more labor efficient than for small tunnels. Working room is available in large tunnels to allow efficient muck removal without delays. Disruption and delays are frequent in small tunnels because of limited working space.

136. On the Kerckhoff 2 power tunnel currently being built, advance rates have averaged about 66 ft/day (Tunneling Technology Newsletter, 1982). This 24-ft-diam tunnel is being driven through hard granite (UC strengths ranged from 8-24 ksi) using one of the most powerful Robbins TBM's ever built. The maximum daily advance has been 137 ft. Availability of this machine has been 70-85 percent which is impressive. Other pertinent data on this tunnel is given in Appendix C.

137. On one of the well publicized TARP tunnels, average excavation rates of 46 ft/day allowed the joint venture contractor to drive the 35-ft 4-in.-diam tunnel through 17,744 ft of dolomitic limestone in 383 days. The TBM averaged 57 percent availability during the entire job. This 810-ton Robbins TBM was driven by twelve 200-hp electric motors and set record excavation rates of 1,743 yd^3 for a single shift and 4,285 yd^3 in a 24-hr period.

138. Rutschmann (1980) discussed TBM utilization for 9 tunnels bored through rock ranging from sandstone to shale to hard limestones to granite and gneiss. Actual average project utilization ranged from 25-75 percent. Utilization rates were highest for a 3.30-m tunnel through limestone. Most of these projects had average utilization factors in the lower part of the given range of 25-75 percent; five of the nine projects had average utilization factors between 25-32 percent.

139. Lange (1979) described a tunnel project in the German Harz Mountains that used a slurry muck-handling system and a Demag TVM21-23 7-ft-diam TBM. In this tunnel, availability averaged 40 percent. The 60 percent of time for which the TBM could not be used was accounted for as follows:

maintenance, changing cutters, and extending slurry pipe, 16 percent; mechanical conveyor breakdowns, 6 percent; hydraulic conveyor breakdowns, 9 percent; TBM breakdowns, 11 percent; unexpected adverse geological conditions, 15 percent; other problems (power failure), 5 percent.

140. Of interest in this case is the serious problems caused by unexpected poor rock conditions. The Demag machine had been designed for good hard rock and had no provisions for installation of support near the face. When an extensive fault zone 650 ft long was hit, the progress was very difficult, dangerous, and slow. After about 300 ft had been driven through this zone with the TBM, the contractor changed to drill and blast methods to get through the fault zone. The TBM was then brought back up to the face to finish the 16,000-ft tunnel.

141. After poor initial performance, the slurry muck removal system was debugged and performed well for most of the drive. The author stated that the system was as reliable as other conventional systems. However, initial costs and operating costs for the slurry system were higher than costs for conventional rail haulage.

142. The author reported best daily advance of 91 ft, best weekly advance of 410 ft, and best monthly advance of 1225 ft.

143. McFeat-Smith and Tarkoy (1979) compared performances of two tunnel boring machines in various rock types. The Robbins 123/133 TBM (Figure 16) was built about 11 years ago and was equipped with single discs to cut the 12-ft 3-in.-diam tunnel. The other TBM was a Demag TVM 3438 (Figure 17) with triple discs and button cutters. The Demag TBM utilization factors ranged from a low of 17 percent for mudstone where severe support problems were experienced, to 56 percent for massive limestone. TBM maintenance accounted for 0.6-2.7 percent of the downtime, cutter replacement accounted for 1-11 percent of the downtime, track and invert unit placement accounted for 2-6 percent of the delays, train switching accounted for 2-8 percent of the delay time, and extension of services about 0.2-8 percent of the delays. Delays due to alignment and grade control were negligible. For the Robbins TBM, utilization ranged from 23-43 percent. Delays were caused mainly by machine maintenance (4-13 percent), cutter replacement (2-11 percent), and in some cases, support placement (0-29 percent). Support placement was a serious bottleneck in the mudstone tunnels. More complete data on these cases is given in Appendix C. Other cases are summarized in Appendix C but are not discussed here.

144. Costs were reported by Bennett (1981) for three TBM-driven rock tunnels. Buckskin Mountain tunnel is a 22-ft-diam, 35,910-ft-long water tunnel driven through granite and complex volcanic rock in Arizona. This U. S. Bureau of Reclamation tunnel was completed in 1980. Total cost of this tunnel was approximately $60,000,000 or $1,671/ft, including lining, which consisted of precast concrete segments.

145. Park River tunnel is 22 ft in diam, 9,100-ft-long, and was driven through sandstone and shale below the city of Hartford, Connecticut, by the U. S. Army Corps of Engineers. Cost for this tunnel completed in 1980 was about $1,590/ft, including lining but not shaft costs.

146. Nast tunnel, a 10-ft-diam, 15,700-ft-long, U. S. Bureau of Reclamation project was completed in 1973 and was one of the first hard-rock tunnels driven by a TBM in the United States. Cutter bit and bearing replacement costs were major factors in the overall $7.5 million cost of this tunnel, accounting for about $2 million of the total. Cost per foot of this tunnel was about $477 (1973 dollars). Again, the cited costs and advance rates are offerred only as examples; actual costs and advance rates for any given tunnel project depend on too many factors to make generalizations meaningful.

Summary

147. In summary, the use of TBM's yields distinct advantages over the use of other methods in terms of high advance rates, reduced tunnel section and reduced overbreak, smooth wall excavation, decreased disturbance of rock, early and simple installation of supports, more uniform rock restraint, and for some machines, reduced caving at face. These advantages are most likely to occur in uniform ground and/or when the selection of TBM type has been matched to anticipated bad rock conditions. TBM's are highly sensitive to geologic conditions such as overstressed rock, unstable and mixed face conditions, water inflow, and squeezing ground. Overstressed, sheared or fractured rocks with low rock mass strength and marginal stability significantly decrease advance rates. For these rocks, the rate of support installation will control advance rates. Supports must be installed quickly to minimize deformations. Excavation should proceed as quickly as possible through such zones. Unstable and mixed face conditions present problems similar to those found in soft ground tunneling. In these situations it is important that supports be installed quickly to prevent caving. Also, the type of shielding on the TBM is an important consideration in this regard. With respect to high

rates of water inflow, TBM's may be preferable to drill and blast since the latter may require breasting at the face. However, water inflow may result in fines and rock chips being diverted from the buckets and the conveyor and accumulating in the invert. In squeezing ground, TBM's with double telescoping shields are vulnerable to being stuck.

148. Therefore, in considering a TBM for use in blocky or crushed ground or where squeezing might occur, design must be based on the principle of immediate support installation at the face and with provisions for grouting ahead of the face.

Novel Excavation Methods

149. This section addresses rock fragmentation, cutting, and excavation methods which are, for the most part, novel, experimental, and beyond current state-of-the-art procedures. The methods described are those which have been reported in the literature within the last ten years. In most cases, use of these methods would require that several agencies relax or modify regulations. These methods represent varying degrees of applicability to tunnel excavation on the basis of the extent of full-scale field tests which have been conducted. In this regard, spiral drill and blast, projectile impact, and water-jet assisted tunnel boring machines are the only methods described here by which full-size tunnels have been excavated under controlled conditions. Also, certain methods, particularly water jetting, although not a state-of-the-art method in this country, may be considered state-of-the-art abroad. Automated drill and blast and spiral drill and blast, projectile impact, thermal techniques, laser and electron beams, water jetting, mechanical impactors, and chemical methods are described in the following paragraphs and their relative effectiveness is discussed in concluding paragraphs of this Part under "Summary and Comparison of Rock Tunneling Methods."

Automated drill and blast

150. Clark, Ashcom, and Hanna (1980) working under contract to the U. S. Bureau of Mines have developed a conceptual design for a shielded automated drill and blast system (ADBS). This system would use line drilling and small charges in four to eight short holes. As a part of these efforts, an economic analysis was conducted in which ADBS was compared to conventional drill, blast, and muck systems.

151. The proposed ADBS includes the following components (Clark, Ashcon, and Hanna, 1980):

a. "Chassis. The ADBS chassis will consist of dual crawlers to advance the equipment, an apron and gathering arms to semicontinuously muck the broken rock, a conveyor to discharge the muck outby the blast shield, and an upper frame to carry the drill(s), load/blast system(s), control cab(s), and the blast shield support booms.

b. Drills. One or more (depending on the size of the face area) hydraulic drills will be mounted on the chassis frame. Each drill will be operated by controls located in the cab. Hydraulic drills, which have a higher penetration rate than pneumatic drills, will be utilized, with each drill being mounted on its own boom.

c. Load/blast system. The proposed explosive loading and blasting system must be compatible with the total system operation. Two possible systems are proposed for investigation. The first will be patterned after the system which has been employed to date, i.e., detonating cord. A second system to be investigated will employ exploding blasting wire caps which are safe to use and have the required accuracy for simultaneous blasting of adjacent holes.

d. Control cab. A control cab is designed to protect one drill operator and one load/blast operator. The purpose of the cab is to provide a safe, comfortable working environment for the operators. It will be heated or air conditioned as required, and will protect the operators from overpressure, dust, fly rock, and excessive noise. The cab, mounted on the chassis frame, will contain all production and safety controls.

e. Blast shield. Blast overpressure, dust, fly rock, and excessive noise will be contained in the heading by a blast shield mounted at the rear of the chassis. The shield will consist of sections powered by hydraulic jacks, the sections conforming to the shape of the drift. A low porosity foam material will seal the periphery of the shield to the drift; a rubber lining on the inby face will attenuate blast noise. Doors will be provided for the muck opening and a manway. The shield will be attached to the rear of the chassis frame by two hydraulic booms.

f. Ventilation. The heading will be ventilated by means of the tunnel exhaust ventilation system. Except during blasting, the air inby the shield will be exhausted by a pipeline from the shield to the portal where the main fan will be located. The cab(s) will be ventilated by fresh air from outby the shield to circulate inby the shield. An auxiliary fan may be required to clear the face of smoke in the desired length of time."

152. The components described above are illustrated in Figures 22 and 23, plan and section, respectively.

153. The advantages and disadvantages of the proposed system are given below:

Advantages -

- Complete shielding of outby work area.
- Semicontinuous advance at rapid rate allowing support erection close to the face.
- Creates less fractured opening, improving safety and decreasing support requirements.
- Reduced ground vibration, air blast, and noise.
- Operator(s) can remain at the face.
- Few operating personnel, reduced labor cost (urban areas).
- Excavates any tunnel geometry.
- Low cost per foot - projected.
- Incorporates many proven components.

Disadvantages -

- Men continuously remain at the face (currently disallowed by Mining Enforcement and Safety Administration (MESA) and U. S. Bureau of Mines (USBM).
- Complicated rock removal from the face.
- Cannot excavate very small openings.
- Requires skilled labor.

154. The overall results of the technical and economic evaluation of the ADBS as quoted from the reference above are given below:

a. The ADBS advance rate is estimated to be from 25-75 percent faster than the conventional drill and blast method (DBM). The 25-percent increase was used in determining the costs reported below.

b. Bit and explosive cost for the ADBS is significantly higher than for DBM. This higher cost is offset by a faster rate of advance, and lower labor and capital costs per foot.

c. Capital cost for the ADBS is approximately 3 percent higher than for DBM. The system cost would be lower if the ADBS were priced as a unit rather than adding component costs from various conventional systems. ADBS equipment cost, on a per foot basis, is approximately 18 percent lower than DBM.

d. Labor cost per foot for the ADBS, due to a reduced labor force and more rapid advance rates, is approximately 37 percent lower than DBM on a per foot basis.

e. ADBS tunnel support costs are from 0 percent to 9 percent lower than DBM, depending on rock type, due to decreased overbreak which results from controlled blasting.

f. On a per foot basis, total ADBS cost is from 17 percent to 20 percent lower than DBM, depending upon tunnel diameter and rock type.

g. Two additional aspects of ADBS tunneling represent significant yet unquantifiable savings: safety and reduction in materials committed to construction.

Spiral drill and blast

155. Rapidex, Inc., under contract to the USBM and the U. S. Department of Transportation has developed a quasi-continuous, remotely controlled, self-shielded, spiral drill and blast tunneler (Louie, 1973; Peterson, 1974; Peterson, Fisk, and Brooks, 1976; and Peterson, Fisk, and Lundquist, 1979). This technique may be used to produce either circular or horseshoe headings. Figure 24 illustrates the generalized continuous spiral drill and blast concept applied to a horseshoe-shaped heading. Testing was conducted at the White Pine Mine in Michigan at depths of 400 ft in shale, siltstone, and coarse-grained sandstones. These rocks exhibited compressive strengths ranging from 13,000-26,000 psi and were highly jointed with joint spacings less than 6 in.

156. The system, shown in Figures 25 and 26, consists of a blast shield which rotates about a central axis, conventional drills attached to an adjustable arm extending radially from the tunnel center line, an explosive containing pod from which the explosives are fed via a flexible hose into the drill holes, and a mucking system. The operation of the system consists of drilling a radial pattern of holes in a pie-shaped segment of the face behind the shield. The drills are then rotated to a safe portion on the other side of the shield and the explosives are loaded into the holes from the pod and hoses. After loading, the pod and hose system is also rotated to the safe side of the shield prior to firing. Upon firing, mucking is conducted using a three-piece telescoping mucker capable of being moved laterally and vertically. These operations are controlled and monitored by two television cameras, one of which is mounted on the explosive pod and the other on the mucker assembly.

157. Adjacent pie-shaped segments are drilled and blasted in a counterclockwise revolution about the face, as described above, producing a pattern similar to the turn of an auger. The augerlike pattern is produced by the depth of the drill holes. Hole depth is the same for all holes along a given radius from the center line of the tunnel; however, hole depth increases for succeeding counterclockwise radii. The spiral blasting pattern was not an

original development from these tests; it was first developed and patented by Ronald C. Baldwin and assigned to Ingersoll-Rand Company in 1963 (U. S. Patent No. 3,098,641). The method has been used at missile silos in New York and shafts in Sweden (Peterson, 1974). However, these earlier applications did not involve shielding.

158. The results of excavating a 10.7-m long, 0.3-m by 0.3-m horseshoe-shaped heading at the White Pine Mine revealed that the advance rate was dependent upon muck rate (0.463 m/hr) which was similar to conventional drill and blast. This dependence may be seen by comparing drill load, and shoot time/hole (277 sec) versus mucking time/hole (351 sec). Overall advance rate was also slowed by difficulty in locating by remote means previously drilled holes, particularly those holes near the tunnel floor. Generally, these and other smaller technical problems can be overcome by improved design of the subsystems and more importantly, by better integration of the subsystems.

Projectile impact

159. Tunnel excavation using high-speed projectile impact has been described by Lundquist (1974) and Watson and Lundquist (1974) from experimentation conducted by Physics International Company under contract to the USBM and the U. S. Army. The techniques of tunnel excavation described include the use of smooth-bore cannons firing high-velocity, solid concrete or steel projectiles. Field tests were conducted at the Hope Valley Test Site in California. The project is known by the acronym REAM (Rapid Excavation and Mining).

160. The cannons used in the project were 57-mm towed and 90-mm and 105-mm self-propelled field guns (Figure 27). The 90-mm gun used a 12-lb charge of conventional cannon propellant to accelerate an 8.5- to 10-lb projectile to a muzzle velocity of 5500 ft/sec. The projectiles (Figure 28) included concrete encased in plastic tubing and pointed steel projectiles. The 57-mm gun was used primarily for trimming. Field tests were conducted in granodiorite having an unconfined compressive yield strength of 25,000 psi and an average joint spacing of 6 ft.

161. During initial testing, a 13-ft-diam portal and preliminary tunnel was established for a length of 20 ft using conventional drill and blast methods. The tunnel was extended to a length of 26 ft using the 90- and 105-mm guns which stood back from the tunnel face at distances of 25-100 ft.

The size of the gun carriage precluded positioning the gun within the tunnel and hence firing was conducted outside of the portal (Figure 29).

162. During subsequent testing, the tunnel was extended to a length of 55 ft using a 90-mm gun attached to a gun carriage which was designed to permit access of the gun into the tunnel. Also, a muzzle blast suppressor or silencer was added to the gun (Figure 30) and a 3/4-in.-thick steel barrier was built in the tunnel behind the gun. Noise level testing of both the silenced and nonsilenced guns indicated that the silencer significantly reduced both noise levels and dust production, and that no hearing protection was needed behind the barrier. A 4000-cfm blower was used to ventilate and exhaust the tunnel which could be accomplished in 2-3 min.

163. The testing demonstrated that the cannons could successfully accomplish tunnel excavation without significant overbreak or damage to the guns themselves. The size of muck produced ranged from dust to rocks weighing up to 1000 lb; however, most muck weighed between a few up to a few tens of pounds and was considered similar to that produced by drill and blast methods. Approximately 1-1/4 to 1-1/2 tons of rock were broken by each shot and 590 shots were fired.

164. Projections based upon the results of these tests and upon the development of an integrated REAM system (Figure 31) indicated that these excavation methods would be three to seven times faster and two-thirds the cost of drill and blast. Also, upon selection of a suitable liquid propellant, the cost per shot could be less than $3. Generally, these projections are based upon tunneling in hard ground requiring little support.

Thermal techniques

165. Rock melting and related thermal methods applied to tunneling include tunnel excavation (Rowley, 1974, Rowley et al., 1974, and Altseimer, 1974), rock fragmentation (Thirumalai and Cheung 1974 and Clark and Lehnhoff 1974), and rock coring (Black 1978 and Altseimer 1974). Cook and Harvey (1974) and Fogelson (1974) have compared these techniques to other nonconventional as well as conventional practices.

166. Studies of rock penetration by melting at temperatures of up to 1800°K was initiated at the Los Alamos Scientific Laboratory in the 1960's. Test penetrators (called subterrenes) up to 114 mm in diameter have been successfully used in many types of rock. These techniques provide the three major elements of the conventional excavation process, namely, advancing hole,

supporting the wall, and removing the debris. Melting consolidating penetrators (MCP's) use density consolidation for melt disposal and rely upon the porosity of rock or soil. The rock or soil melt is formed into a glass lining which is accommodated by the larger melted hole diameter. Universal extrusion penetrators (UEP's) were developed for melting holes in dense rocks; however, they also can be used in other rocks and soils. The molten rock confined by the unmelted rock and the hot face of the penetrator, is continuously extruded through the hole in the melting face. Consolidated coring penetrators (CCP's) incorporate techniques of MCP's and UEP's and are used to obtain continuously retrievable and geologically useful core samples. Plans were made for a 300-mm-diam device called the Geoprospector which will produce 200-mm-diam cores. John H. Altseimer and Robert J. Hanold have patented a concept and tunneling apparatus for producing hard rock tunnels ranging in size from 2 to 12 m or larger and which is nuclear powered (U. S. Patent No. 3,885,832, May 27, 1975, assigned to U. S. Energy Research and Development Administration). They have also patented a similar device for soft ground tunneling (U. S. Patent No. 3,881,777, May 6, 1975, assigned to U. S. Energy Research and Development Administration).

167. Rock fragmentation can be enhanced by heating rocks to temperatures ranging from 500°-800°C. Heating to these temperatures produces tensile stresses which, if combined with other techniques such as water-jetting, can effectively break down rock masses. The thermally produced stresses produce both microcracking and macrocracking which can be propagated through the rock mass. However, heating alone is not efficient in terms of energy conversion and thus, this technique would be best applied in conjunction with hydraulic or mechanical methods. Heat may be applied at the rock surface or, more effectively, from within the rock mass. Heating to these and higher temperatures depending upon whether fragmentation or cutting is required can be accomplished by means of high frequency fields, microwaves, resistance wire and electric arc heaters, plasma torches (20,000°C), flame jets, infrared heaters, lasers, and electron beams. Lasers and electron beams are discussed separately below.

Laser beams

168. Jurewicz, Carstens, and Banas (1974) and Cook and Harvey (1974) have reported the use of high-power lasers in rock cutting. The laser gun tested was a 1- to 6-kw, electric discharge, convectively cooled, CO_2 gas

laser serving as an amplifier for a Gaussian input beam of 100 w. The input beam was focused by means of mirrors. The purposes of these tests were to: (a) determine the effects of rock type, (b) evaluate the type of focusing system required, (c) investigate the laser power levels necessary for cutting, and (d) evaluate the effectiveness of line-focusing as opposed to spot focusing. The results showed that at slow kerfing speeds (2.12 cm/sec) fine-grained igneous rocks could be penetrated deeper than coarse-grained igneous rocks; however, at faster kerfing speeds (8.5 cm/sec), penetration depths were lower and less dependent upon rock types. The bombardment of the laser beam produces rock melting and induces thermal stresses resulting in cracking. Generally, the tests showed that with a given power level, the optimum focal length was a function of kerfing speed. Line focusing was accomplished with a cylindrical focusing mirror which restricted curvature to one plane. Line focusing was found to result in a 39 percent decrease in kerfing energy. Economic analyses indicated that laser gage kerfing may offer economic advantages over other methods depending upon rock type, tunnel size, and laser technology.

Electron beams

169. The experimental use of electron beams to fragment or cut rock has been described by Avery et al. (1974), Schumacher and Smith (1974), and Cook and Harvey (1974). Rock shattering and fragmenting will occur when a rock surface is bombarded by submicrosecond bursts of high energy (1 MV) electrons delivered by an electron accelerator. The electron bombardment produces an average temperature rise of 155°K (for granite) and an average initial compressive stress of 15 ksi within a small volume of rock. Elastic stress waves propagate beyond the initially overstressed volume and, in some cases, spalling can occur at the front and rear of 1-cm-thick samples. Overall, the tests show that spalling can be produced in a variety of wet or dry rocks and clay, with soft and/or wet materials spalling better than dry ones; that the debris consisting of dust, sand, or small flakes, may be easily removed; and that with additional research, the process may be applicable to tunneling.

170. The use of a collinated continuous electron beam directed toward a rock surface will transfer sufficient energy to the rock to cause quasi-adiabatic melting and vaporization. The electrons produce a pear-shaped hole in the rock and thermally induced stresses which induce cracking and breaking. Spalling and kerf-cutting can also be produced in some rocks and with certain

types of electron beams. The use of these techniques to break blocks and ledges will result in an energy expansion per unit of muck produced which complies favorably to that of other methods. These techniques alone may someday be useful for tunneling and/or in conjunction with other mechanical or hydraulic techniques.

Water-jetting

171. The application of high-pressure jets in rock fragmentation and excavation has been described by Summers and Barker (1976), Wang and Miller (1976), Olsen (1980), and O'Hanlon (1981), and reviewed by Janakirim and Symala Rao (1982). Cook and Harvey (1974) have compared water-jetting to other excavation and fragmentation methods. Generally, high-pressure water-jetting has been applied in rock boring, particularly oil well drilling, and in foreign coal mining. O'Hanlon (1981) has reported the development of a production prototype of a water-jet roof bolt drill for use in coal mines. Although, as reported by Janakirim and Symala Rao (1982), water-jetting was first used in 1930 for the construction of the Moscow Subway, this technique has not had widespread application in tunnel excavation. However, O'Hanlon (1981) wrote of "a novel, non-explosive, rock fracture method utilizing high-pressure water-jet equipment. This method enables massive rock to be excavated at rapid rates from a single work face. Based on initial tests, two men using quiet, lightweight hand-operated tools weighing 15-25 lb each can achieve excavation rates of 20,000-30,000 lb of rock per hour, with typical rock fragments ranging from 200-500 lb each." Market introduction is expected in the near future.

172. The mechanisms of water-jet cutting involve erosion of the rock face by developing shearing forces which are greater than the cohesive forces which bind rock grains together. Also, for permeable rocks, water entering pore spaces will produce large pore pressures which will contribute to rock fragmentation. Thus, permeability and water content are important aspects of the overall process. The mechanisms are efficient due to the large energy which is transferred over a small area. The type of fragmentation and the details of the mechanism producing the fragmentation are a function of nozzle configuration and whether the jet is continuous or pulsed. With selected nozzles, for example, cavitation can be produced, also, pulsed water-jets produce drilled holes rather than broken rock. The specific energy of water jetting is a function of nozzle size, pressure, and other properties of the fluid, traversing rates, and rock properties.

173. The effectiveness of water-jetting used in conjunction with other excavation techniques has been shown to be considerable. With respect to disc cutters used with water-jets, investigations have shown that jetting permits lower static pressures applied to the discs and thereby increases disc life. Water-jetting has also been shown to be effective when used with thermal methods of rock fragmentation (see "Thermal techniques"). Perhaps the greatest potential for water-jetting pertains to its application in conjunction with coal mining machines and tunnel boring machines (TBM's). Summers and Barker (1976) have designed and constructed a longwall coal mining machine called the Hydrominer. The machine design consists of the modification to the extent possible of existing equipment on a Meco Moore miner and standard off-the-shelf pumps and water supply systems. However, considerable alteration and redesign of the cutterhead was involved. Although not field tested (in 1976), the Hydrominer was expected to operate with water pressures of 10,000 psi, on coal seams approximately 5 ft thick traversing 15 ft/min, and producing 6 tons of coal per minute.

174. Wang and Miller (1976) have reported on the laboratory and field testing of water-jet assisted tunneling in conjunction with a 1963 vintage, 7-ft-diam Robbins TBM. Field work and tunneling were conducted in a granite quarry near Skykomish, Wash. Minor modifications were made on the cutterhead, cutter supports, and hydraulic system of the TBM in order to accept the water nozzle manifold (Figure 32). A high-pressure swivel was designed to transfer water from the pump to the manifold in the cutterhead. The water pump and intensifier were designed to develop 56,000-psi water pressure. The TBM was set up inside a blasted, initial section of tunnel and the cutterhead was advanced without water-jetting at 4,000-, 3,500-, and 3,000-psi cutterhead thrust pressures in order to develop an expected performance curve. Advances were subsequently conducted at 3,250- and 3,750-psi thrust pressures; advance rates at these pressures were found to plot on the performance curve. Advances were then made using water-jetting for approximately 15 min followed by unassisted mechanical cutting of the same duration. This sequence was then repeated.

175. The field tests showed that water-jet assisted tunneling could be conducted in hard rock with a 50-60 percent increase in advance rates, and in some cases, advance rates could be doubled. Also, there was an approximate 25 percent reduction in torque apparently due to decreased friction on

the cutterhead. Comparative economic analyses conducted as a part of the study indicated that a 50 percent increase in advance rate would result in 14 and 26 percent cost savings for 10-ft and 20-ft-diam tunnels, respectively.

Mechanical impactors

176. The fragmentation and excavation of rock by means of the impact of mechanical picks, discs, and impact hammers have been described by Roxborough and Phillips (1974), Evans (1974), Voitsekhovskii (1974), Grantmyre and Hawkes (1975) and Wayment and Grantmyre (1976). Shaft excavation by mechanical impactor is discussed in Part III. Cook and Harvey (1974) and Fogelson (1974) discussed these methods and compared them to conventional excavation methods. Generally, mechanical impactors have been more extensively used in mining, particularly coal mining, than in tunnel excavation. Rock fragmentation is believed to be caused by tensile stresses induced by picks and by shear stresses induced by the rolling action of discs and the percussion of impact hammers.

177. With respect to picks, excavation efficiency has been studied in terms of pick shape and size, rake and clearance angles, depth of cut, cutting speed, and pick spacing; and empirical equations were developed relating these factors to tool forces and yield and specific energy. These relationships were found to be useful in estimating pick performance on the sandstone tested (Roxborough and Phillips, 1974). In related studies, Evans (1974) determined that the specific energy (energy per unit volume of broken rock) developed by picks can be calculated in terms of pick geometry and tensile strength of the rock. In comparing pick versus disc cutters, picks may be disadvantageous due to incentive sparking and to the production of airborne dust; whereas, discs require considerably more energy than picks. Rock type is also a factor in choosing between picks and discs; for example, the ratios of specific energies for disc/pick cutting are unity for shaly rocks and between two and five for sandstones.

178. High-energy percussion methods of rock fragmentation such as hydraulically controlled, mechanical impactors exhibit a low specific energy (similar to picks and discs) and, thereby, high efficiency which is only exceeded by drill and blast methods. The impactor or gun is several feet long and can be attached to a boom mounted on a tractor or other vehicle suitable for above ground or tunnel work. Figure 33 is a schematic of the impactor gun and Figure 34 shows a Joy underground impactor as described by Wayment and

Grantmyre (1976). Machines similar to the one illustrated have been tested above and below ground on a wide range of rock types; however, no linear relationship between machine effectiveness and rock properties could be determined.

Chemical methods

179. Fogelson (1974) has reviewed the use of chemicals in dissolving and/or as an aid in mechanically fragmenting rock. Perhaps, the most experimental or applied use of chemicals has been in rock drilling where tests have shown that certain chemicals when added to drilling fluids appreciably increase drilling rates in some rocks. The chemicals used in these tests included sodium azelate solutions and nonionic, anionic, and cationic surfactants and were reported, in some cases, to decrease bit or tool wear. Although the use of chemicals in tunnel excavation has not been widespread, the evidence would suggest that this method may be useful in combination with water-jet assisted TBM's.

Summary and Comparison of Rock Tunneling Methods

180. The only extensively used methods for driving rock tunnels are the drill and blast and machine tunneling methods. There are wide variations in practice for each of these general methods, depending on geological conditions, owner requirements, contractor preferences, and other factors. Drill and blast excavation has been the method by which all others have been judged for driving tunnels through rock. This method is quite versatile and can be readily adapted for changing rock conditions, an obvious advantage over full-face TBM's which depend on uniform conditions for good progress. Partial-face machines are adaptable to changing ground conditions but are limited to use in soils and soft- to moderate-strength rocks. The drill and blast method enjoys the advantage over machine-driven tunnels of much lower capital costs for equipment. In addition, drill and blast tunnels do not require miners to be as well trained as the crew for a machine-driven tunnel must be. However, fewer miners are required for machine-driven tunnels. In drilled and blasted tunnels, the working room at the face is adequate for dealing with adverse conditions as they arise. Although access is not a problem with partial-face machine-driven tunnels, access to the face of TBM-driven tunnels is usually severely limited; the machine occupies the entire cross-sectional area of

the face. Consequently, probe drilling ahead of the face and changing cutter bits or bearings on the machine causes disruptions because the machine must be stopped and backed away from the face. More recently, TBM manufacturers have made provisions in some machines for changing the cutters and bearings from behind the face shield*. Also, the provision for probe drilling through a central pilot hole in the machine's face is fairly common now, so excavation does not have to be halted. Another problem that has been dealt with effectively by some machine manufacturers is the installation of supports. Boring machines occupy virtually the entire tunnel cross section for 60 ft or more behind the face. Early versions had no provisions for installing support until the machine had passed. Squeezing or swelling rock or loose blocks falling from the roof or face presented major problems when encountered. More recent machines have included provisions for rock-bolt installation and grouting or shotcrete application very near the face through openings in the roof shield just behind the cutterhead. In addition, a few recent machines have provisions for maintaining face stability. A series of concentric ring beams may be mounted on the cutterhead to prevent loose blocks from jamming the machine.

181. Until recently, drill and blast excavation was <u>the</u> method for driving tunnels through hard rock. TBM's could not effectively excavate hard rock. (Partial-face machines still cannot because of their limited thrust capabilities.) However, research into improved components and their arrangement to allow installation of supports, improved cutterhead design, cutter bits and bearings, hydraulics, and other areas have paid off for machine manufacturers and today, full-face boring machines are being produced that can be effectively used in very hard rock, making them quite competitive with drill and blast excavation.

182. These improvements have led to a sizeable increase in the percentage use of TBM-driven tunnels in rock. The historic advantages of drill and blast methods for hard rock excavation have been challenged and met by modern TBM's. Thus, the choice of excavation method now requires detailed analysis of many factors; among them equipment capital costs, labor requirements and availability, owner requirements, project size, machine delivery lead times, site considerations, geological considerations, and geometry constraints. These considerations were discussed earlier in this section.

183. Cook and Harvey (1974) and Fogelson (1974) have given a review and appraisal of the various innovative fragmentation and excavation methods including most of those presented here and also evaluated them in terms of standard techniques such as TBM's and drill and blast methods. Overall, the relative or absolute effectiveness of a given method must be considered in terms of advance rate which is controlled by the following relation:

$$R = 3{,}600 \quad P/S$$

where

R = penetration rate, m/hr

P = specific power delivered to the face, MW/m^2

S = specific energy, $^{MJ}/_{m^3}$

184. The specific energy is that consumed to break originally solid rock. Plots (Figure 35) of specific energy versus grain size of fragmented rock produced can be made which show an inverse exponential straight-line relationship between these two given quantities for a given rock. However, such plots yield two curves; one curve represents techniques which excavate and the other, techniques which comminute or grind up the rock. Specific energy for excavation increases as fragment size decreases.

185. Cook and Harvey (1974) compare the effects of specific power and specific energy for drilling and drill and blast tunneling using the following example:

	Diamond Drilling	D&B Tunneling
Specific energy	1,120 $^{MJ}/_{m^3}$	5.7 $^{MJ}/_{m^3}$
Specific power	3.8 $^{MJ}/_{m^2}$	1.3 $^{KW}/_{m^2}$
Penetration rate	12 $^{M}/h$	0.83 $^{m}/h$

186. The data tabulated above show that, in this example, the penetration rates are within an order of magnitude; whereas, both the specific power and specific energy of drill and blast tunneling are several order of magnitude less than those values for diamond drilling.

187. Similar data for a variety of TBM's operating in a wide range of rock conditions are tabulated below:

Specific energy	18 - 420 $^{MJ}/_{m^3}$
Specific power	25 - 54 $^{KW}/_{m^2}$
Penetration rate	0.3 - 5.2 $^{m}/h$

188. The data above show that TBM's exhibit a higher penetration rate over drill and blast accompanied by an increase in both specific energy and power over drill and blast; however, the increase in specific energy and power is significantly less than that of diamond drilling. From these examples, it is apparent that for any novel excavation method to be competitive with either drill and blast or TBM's the specific energies and powers of these methods must be similar to that of drill and blast or TBM.

189. Grantmyre and Hawkes (1975) reported specific energies for high-energy, mechanical impactors in the range of approximately 8-165 $^{MJ}/_{m^3}$ which is similar to TBM and drill and blast. However, there are limitations in hammer velocity, weight, and size of the impactors which affects power development, particularly in a tunnel.

190. Cook and Harvey (1974) give specific energy data for water-jetting which range from 0.3 x 10^3 to 33 x 10^3 $^{MJ}/_{m^3}$, significantly higher than either TBM or drill and blast. Similar relations are evident for thermal techniques including lasers and electron beams; however, at least with electron beams, spalling may be more efficient than cutting.

191. Figure 36 illustrates the relations between penetration rate, specific power, and specific energy for conventional and novel methods in which the requirement for high specific power for novel methods is evident. Considering these relations, the applications of many of the novel methods are severely limited to secondary roles in tunnel excavation or to hybrid methods in which they are used to assist a conventional method.

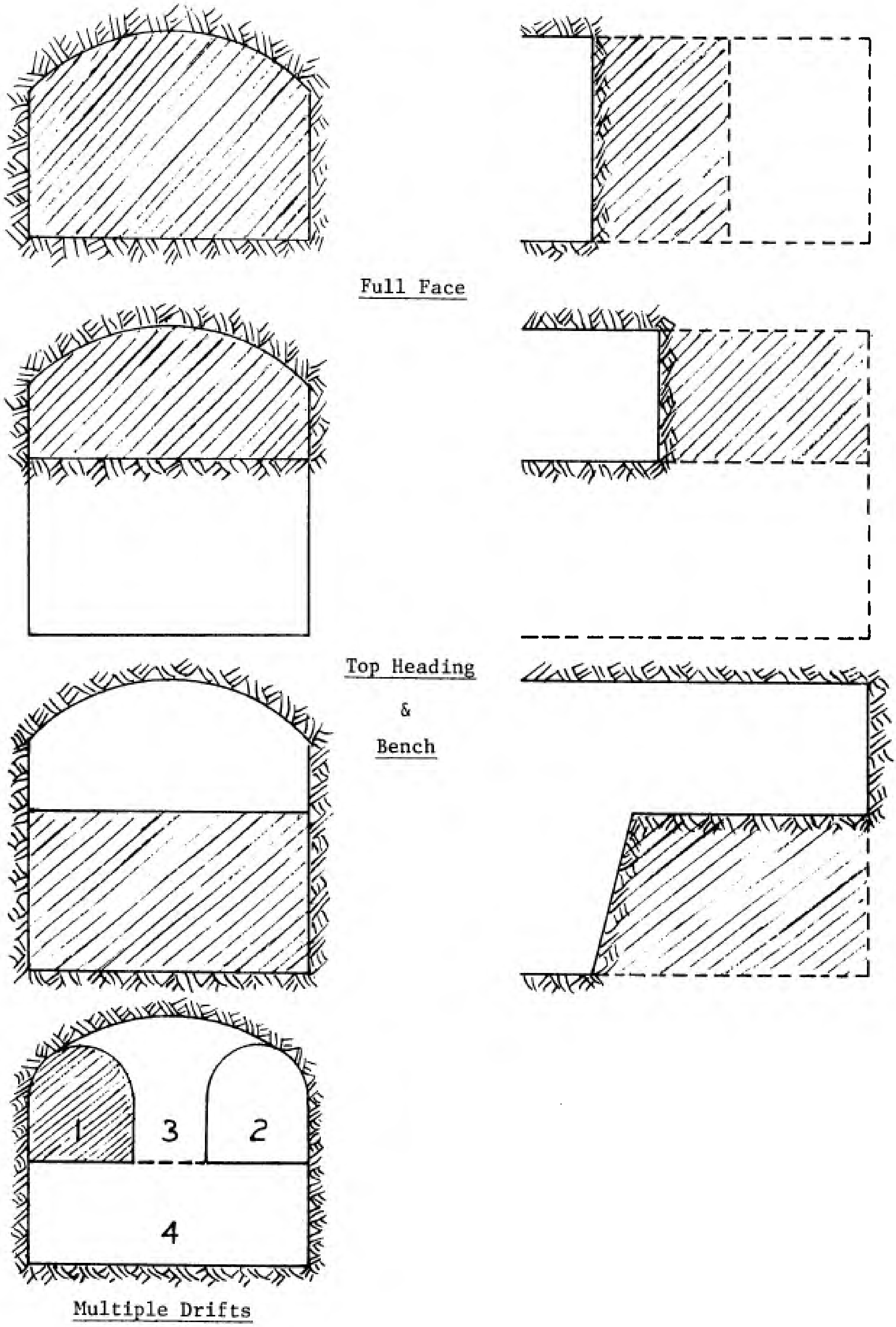
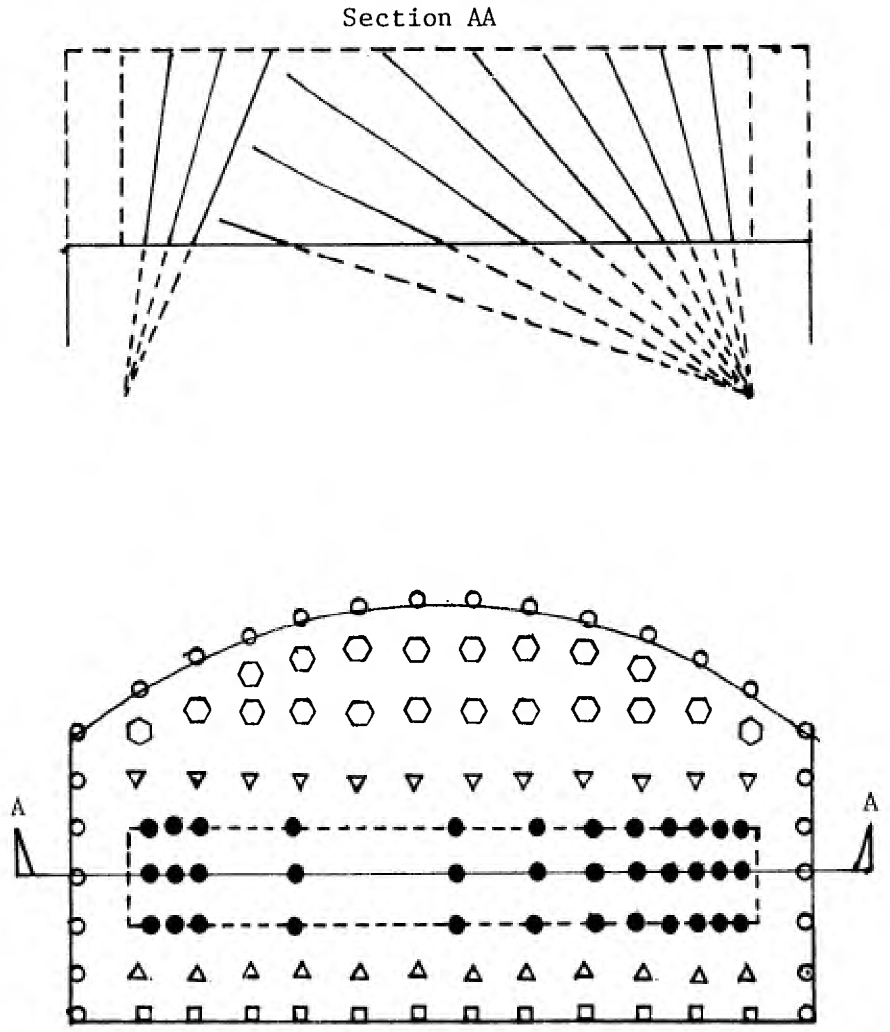


Figure 1. Heading advance options for drill and blast excavation



● Angle Holes

△ Easer or Relief Holes

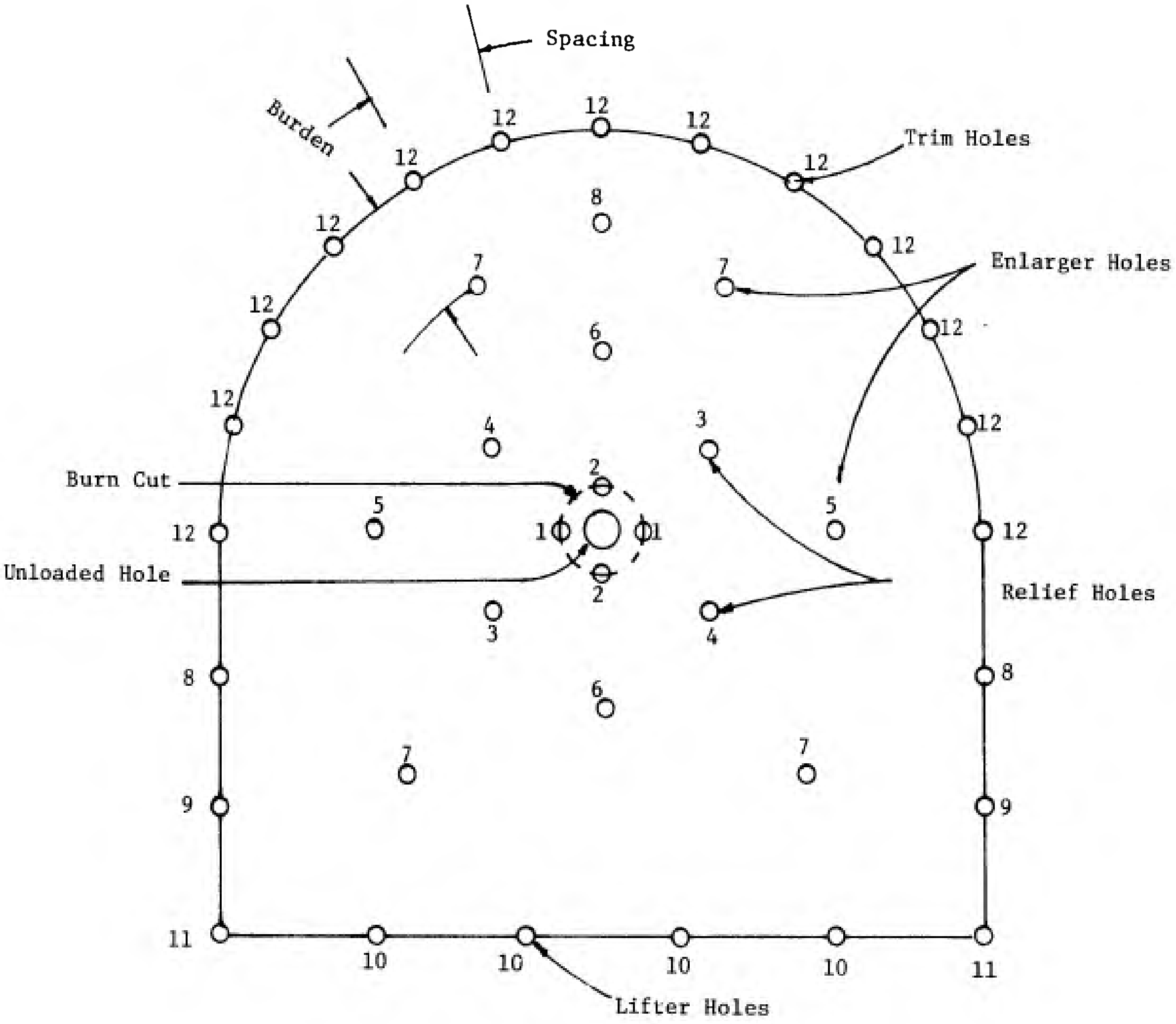
⬡ Enlarger Holes

□ Lifter Holes

○ Trim Holes

a. Angle or pyramid cut

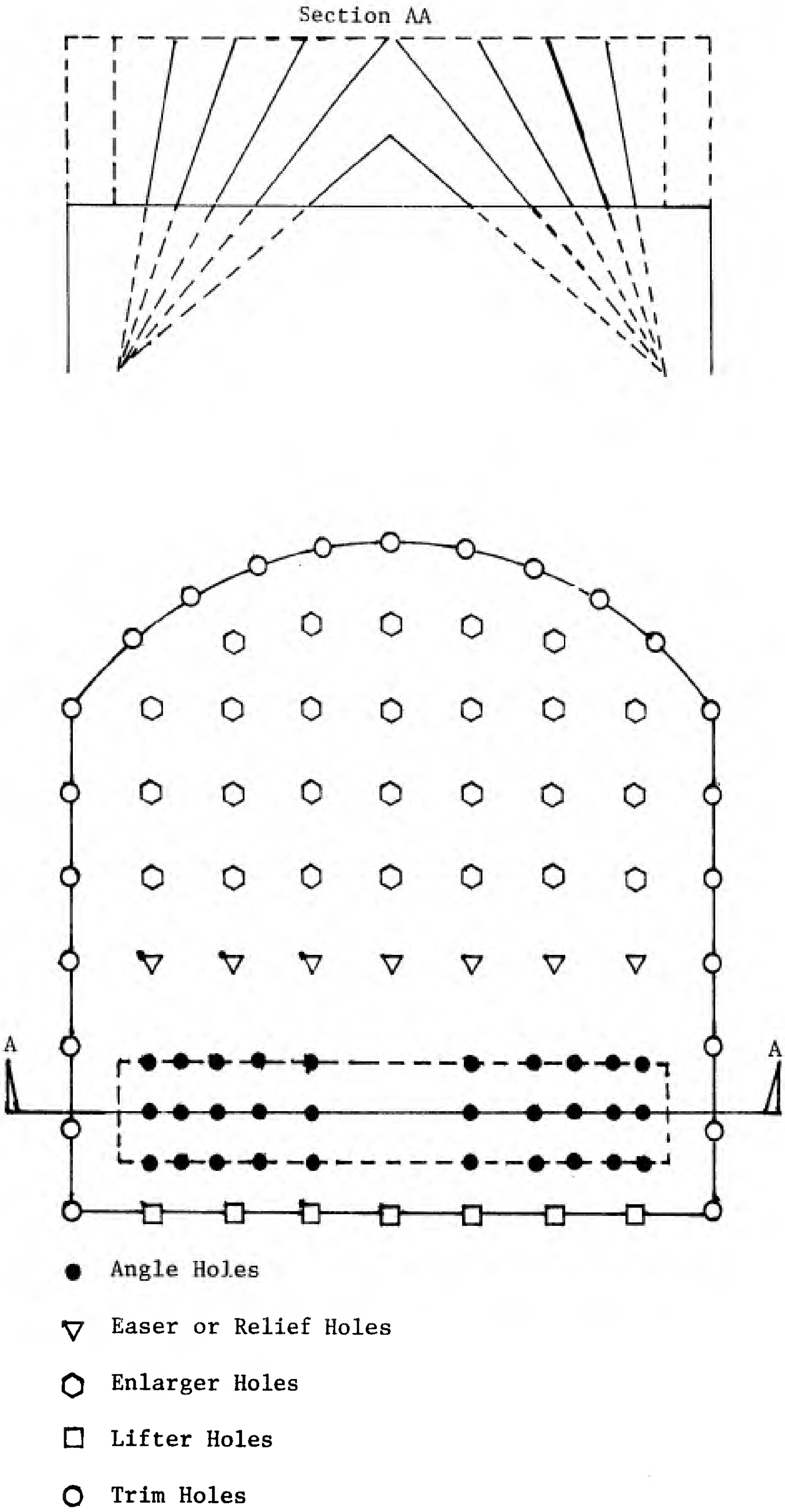
Figure 2. Blasting patterns (Sheet 1 of 3)



Notes:
1. Numbers indicate sequence of detonations at predetermined delay intervals of time.
2. Several sets of relief and enlarger holes may be required in large tunnels.

b. Burn cut

Figure 2. (Sheet 2 of 3)



c. V-plow cut

Figure 2. (Sheet 3 of 3)

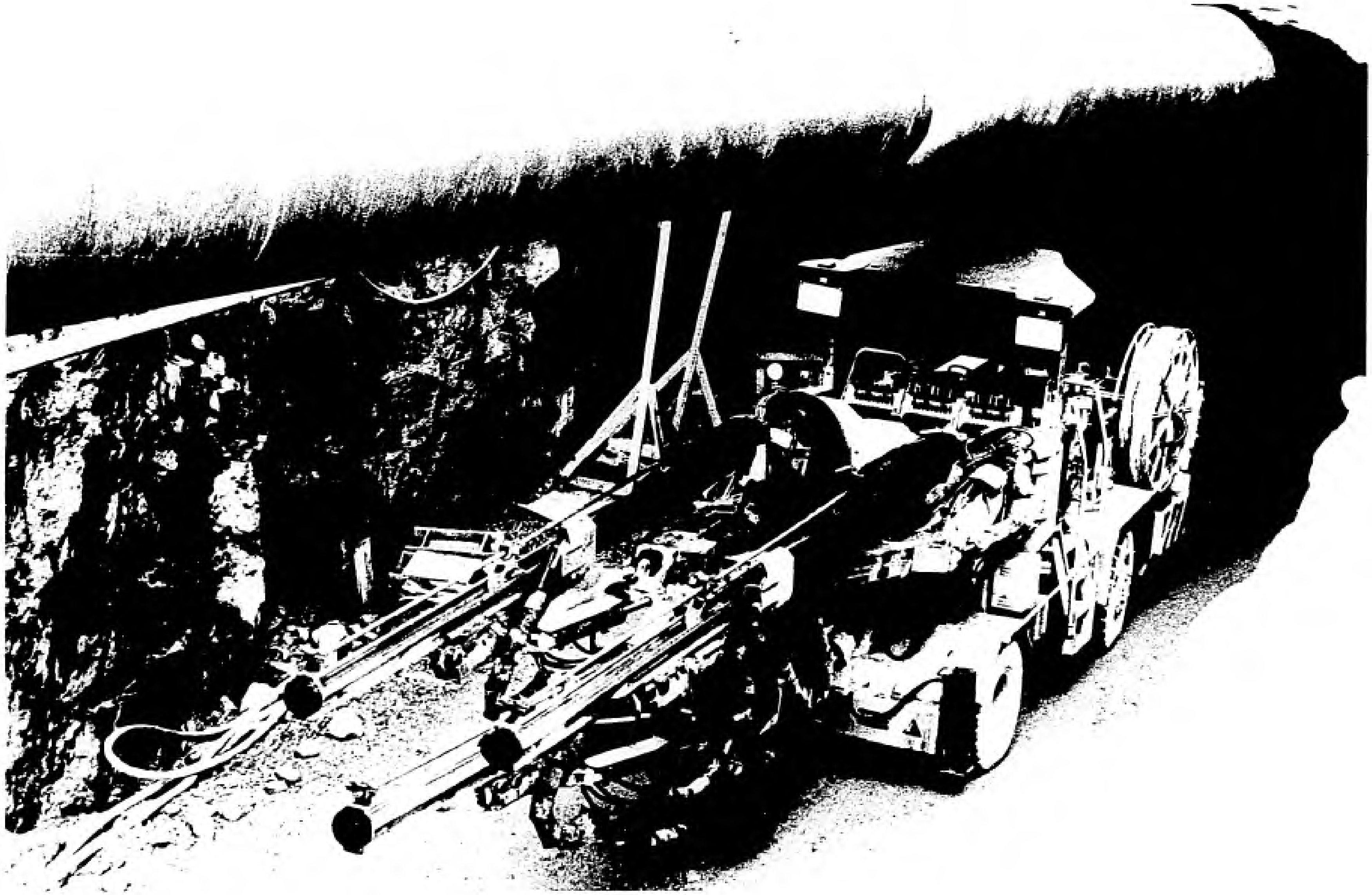


Figure 3. Modern drill jumbo, view 1

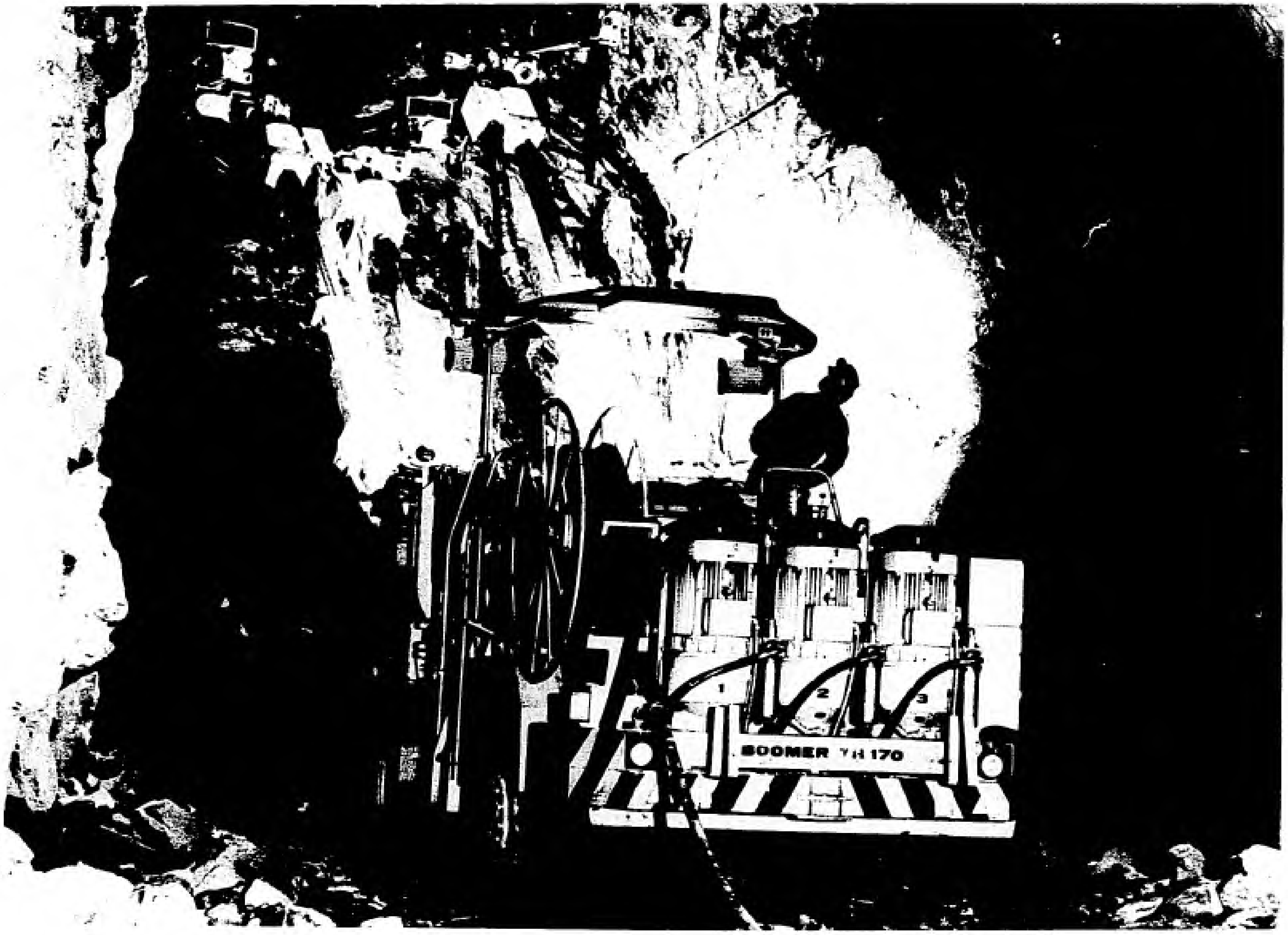


Figure 4. Modern drill jumbo, view 2

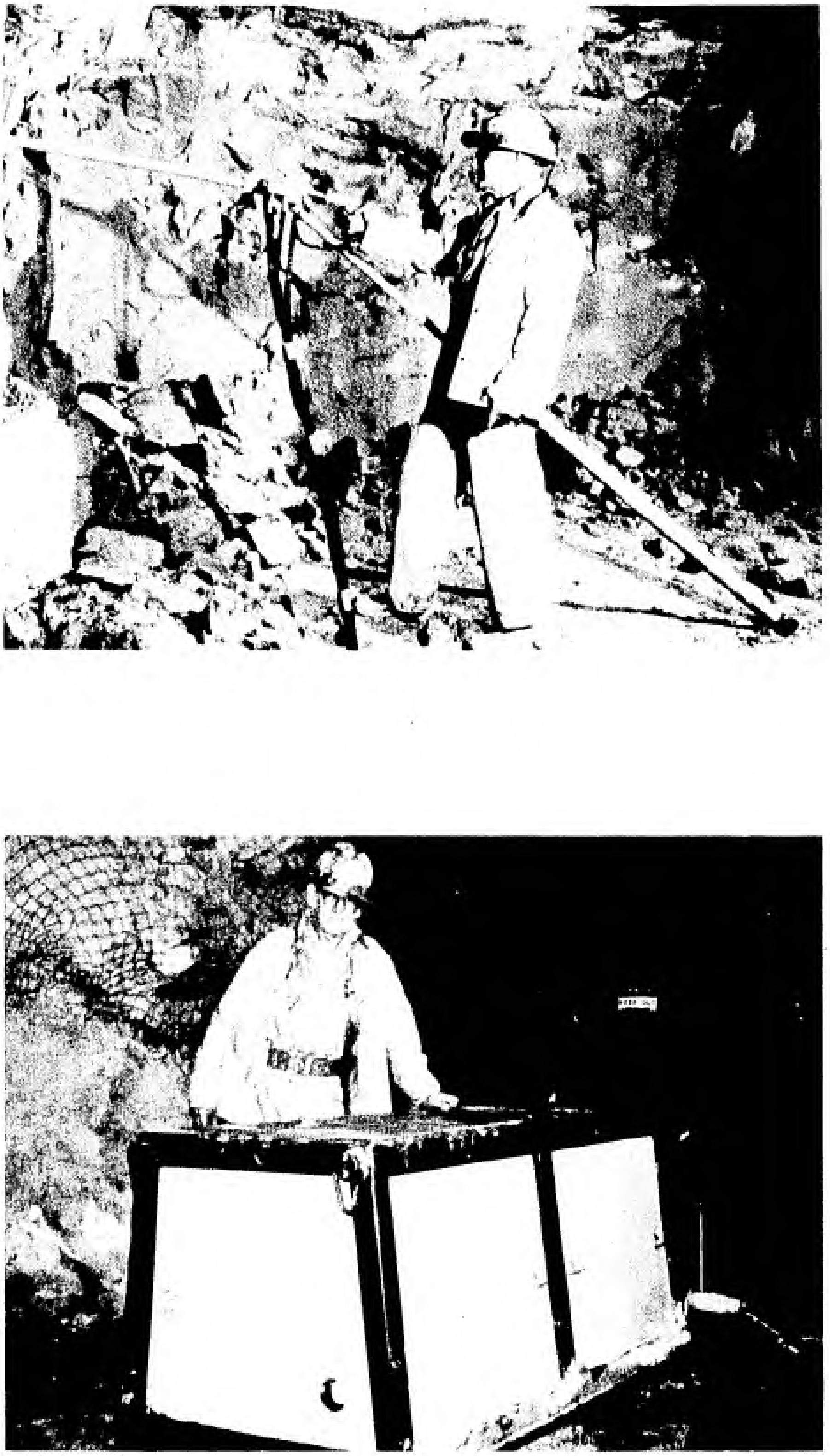


Figure 5. Water jet drill and powerpack
(courtesy of Flow Industries)

Figure 6. Shielded Roadheader

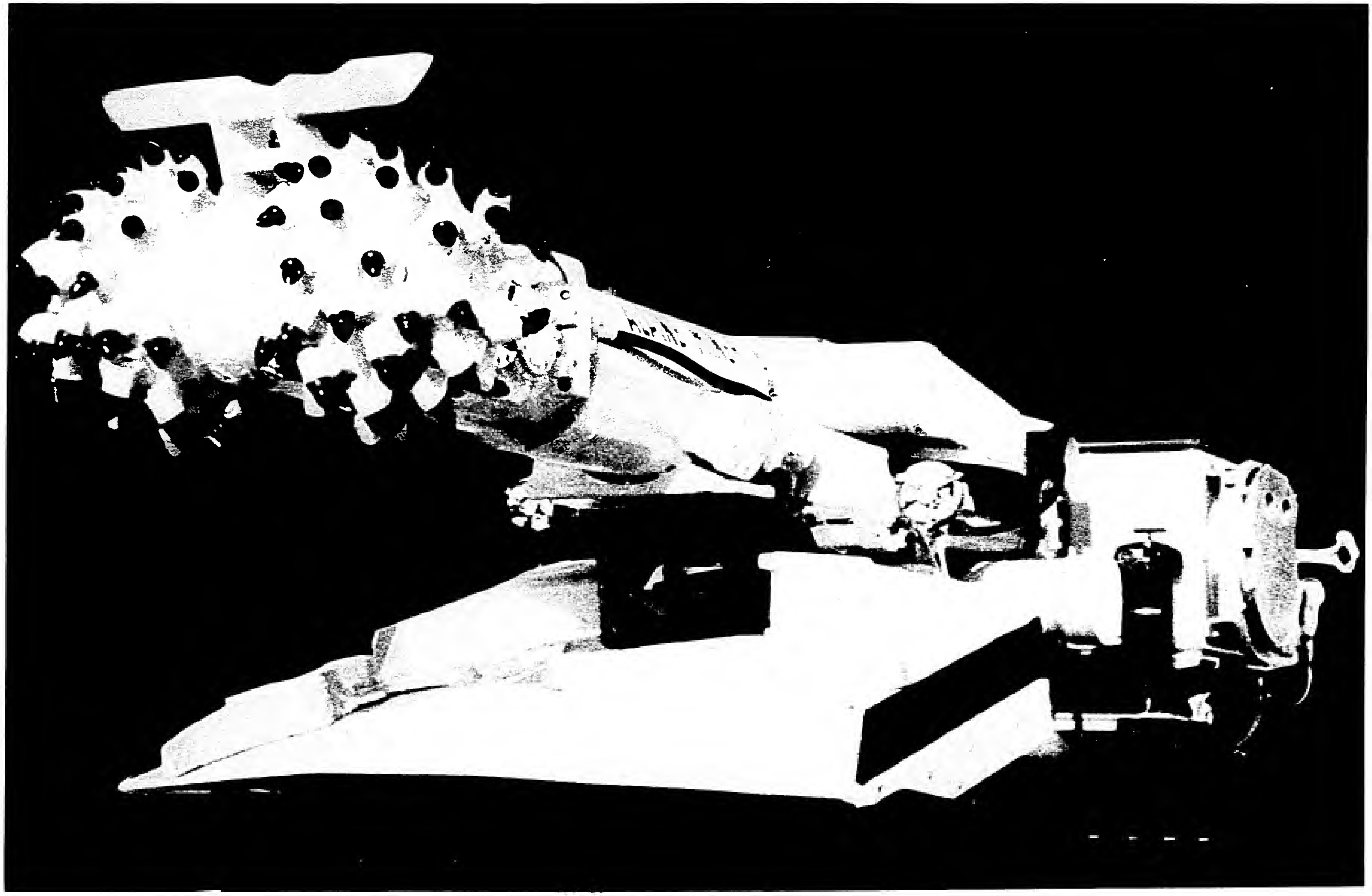
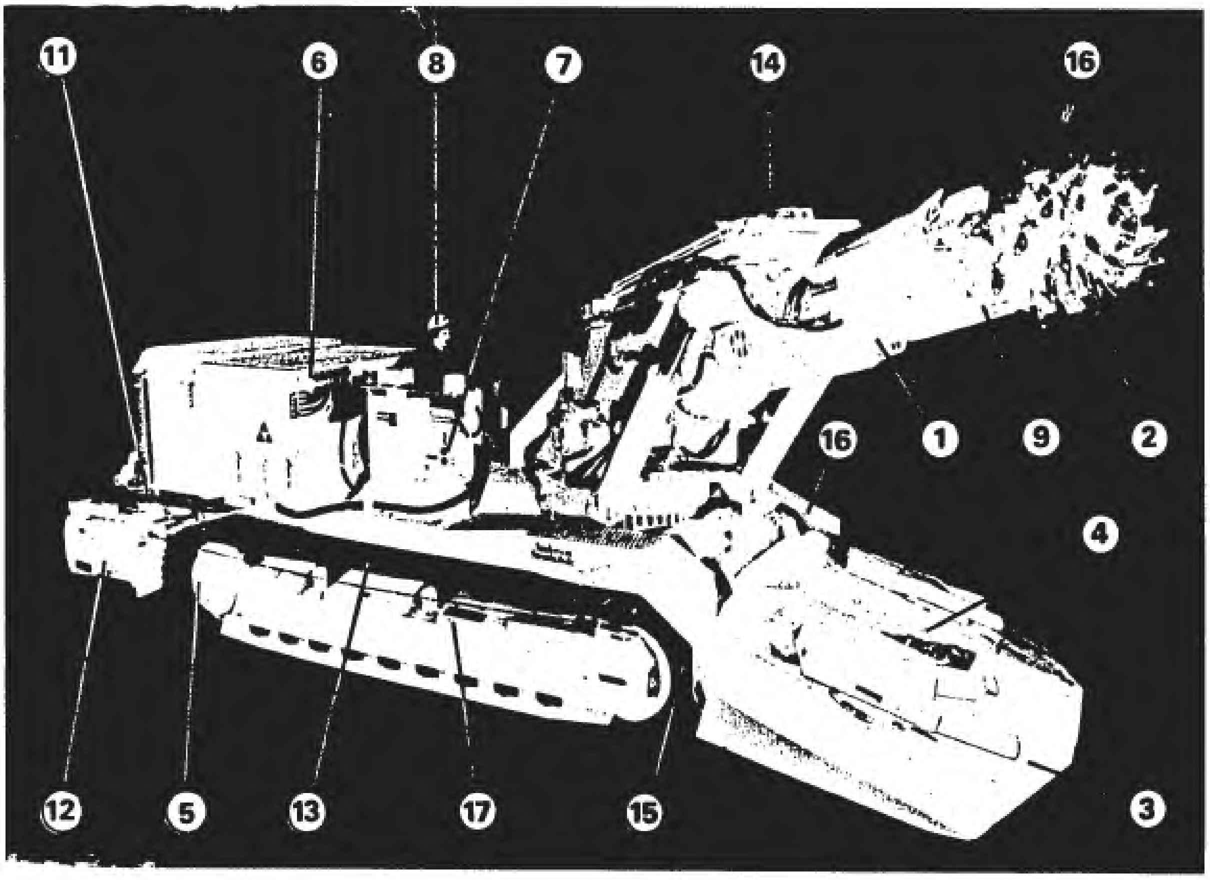


Figure 7. Roadheader for use in rock (courtesy of Voest-Alpine)

Anderson RH1/4



1. **Robust cutting boom** powered by a 112 kW air cooled electric motor driving through a heavy duty gear transmission.

2. **Heavy duty cutting head** designed to suit strata conditions with pick face flushing facility offered as an optional extra.

3. **3.51 metre wide gathering apron** capable of being raised or lowered as required for tramming or spragging and suitable for loading bulky, fine or wet material.

4. **Centre scraper chain conveyor** built for abrasive applications with a large throat and armour plating for maximum wear resistance.

5. **Large crawler tracks** which are independently or bi-directionally operated to give maximum machine manoeuvrability for working on steep gradients and poor floor conditions.

6. **112 kW hydraulic power pack** incorporating temperature and level safety switches.

7. **Electrical controls** built to fully approved flameproof standards for mining use.

8. **Operator station** centrally positioned to give all round visibility with all electrical and hydraulic controls within easy reach.

9. **Telescopic action** to allow cutting head to be sumped in with the machine stationary and therefore independent of floor conditions.

OPTIONAL EXTRAS

10. **Service jacks** mounted at the rear.

11. **Bridge conveyor** mounted under the discharge point of the centre conveyor.

12. **3 ton winch**

13. **Rear floor sprag jacks**

14. **Arch girder and/or work platform**

15. **Front floor sprag jacks**

16. **Dust extraction ducting**

17. **Safety cut outs** for the protection of the associated workforce.

Figure 8. Main components of Anderson Strathclyde roadheader

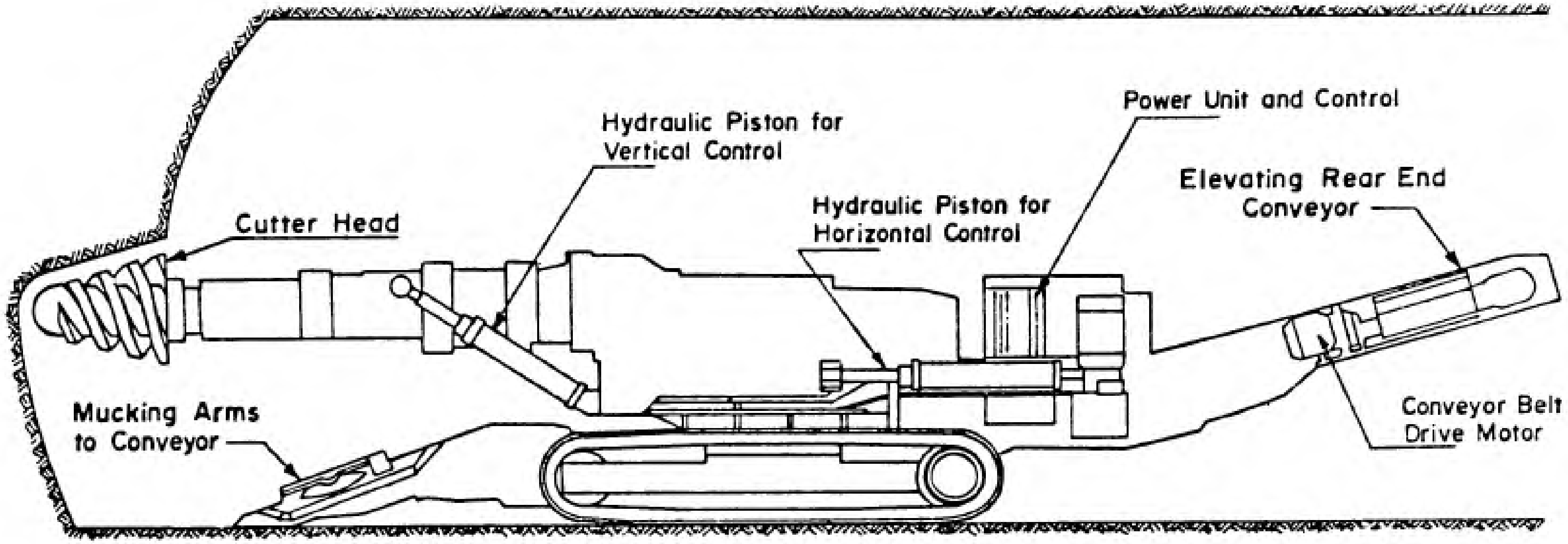
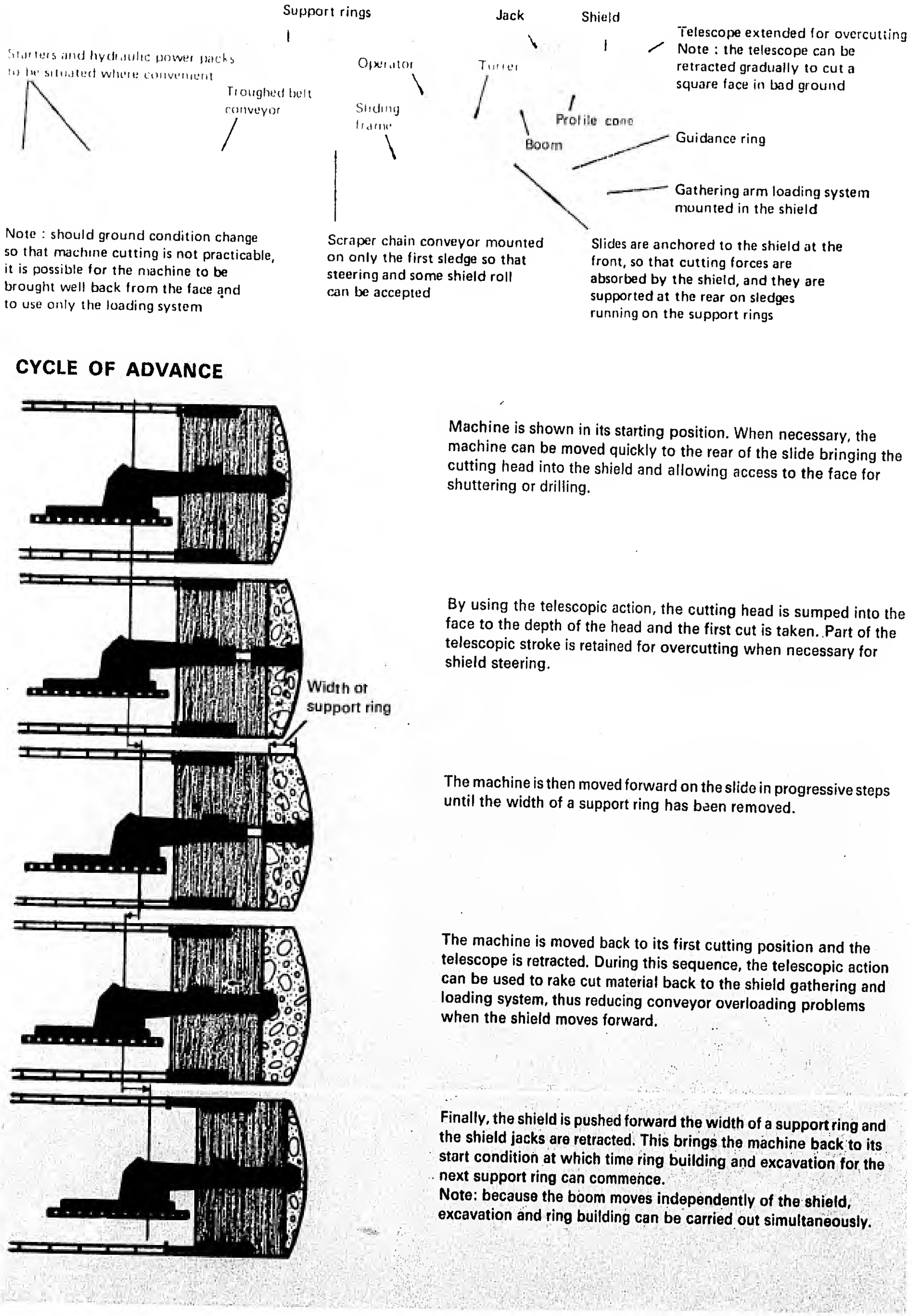


Figure 9. Schematic of roadheaders



Note : the telescope can be retracted gradually to cut a square face in bad ground

Note : should ground condition change so that machine cutting is not practicable, it is possible for the machine to be brought well back from the face and to use only the loading system

Scraper chain conveyor mounted on only the first sledge so that steering and some shield roll can be accepted

Slides are anchored to the shield at the front, so that cutting forces are absorbed by the shield, and they are supported at the rear on sledges running on the support rings

CYCLE OF ADVANCE

Machine is shown in its starting position. When necessary, the machine can be moved quickly to the rear of the slide bringing the cutting head into the shield and allowing access to the face for shuttering or drilling.

By using the telescopic action, the cutting head is sumped into the face to the depth of the head and the first cut is taken. Part of the telescopic stroke is retained for overcutting when necessary for shield steering.

The machine is then moved forward on the slide in progressive steps until the width of a support ring has been removed.

The machine is moved back to its first cutting position and the telescope is retracted. During this sequence, the telescopic action can be used to rake cut material back to the shield gathering and loading system, thus reducing conveyor overloading problems when the shield moves forward.

Finally, the shield is pushed forward the width of a support ring and the shield jacks are retracted. This brings the machine back to its start condition at which time ring building and excavation for the next support ring can commence.
Note: because the boom moves independently of the shield, excavation and ring building can be carried out simultaneously.

Figure 10. Schematic of roadheader excavation method (courtesy Anderson Strathclyde, Ltd)

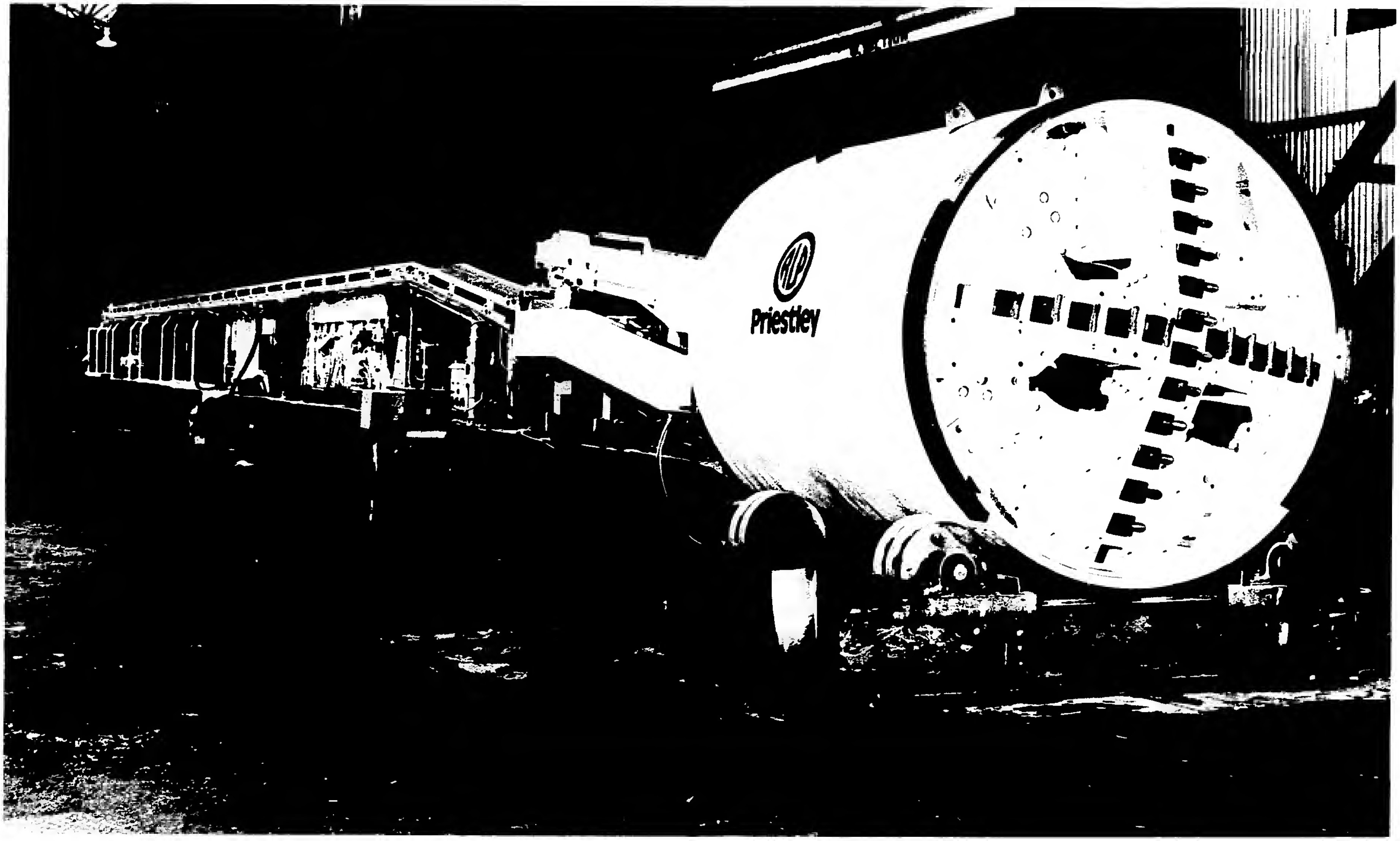


Figure 11. Modern full face tunnel boring machine for soft ground tunnels; note full telescopic shield for support of tunnel. Segmental lining may be erected safely inside this shield, and grouted in place as the machine advances (courtesy of Robert Priestly Ltd)

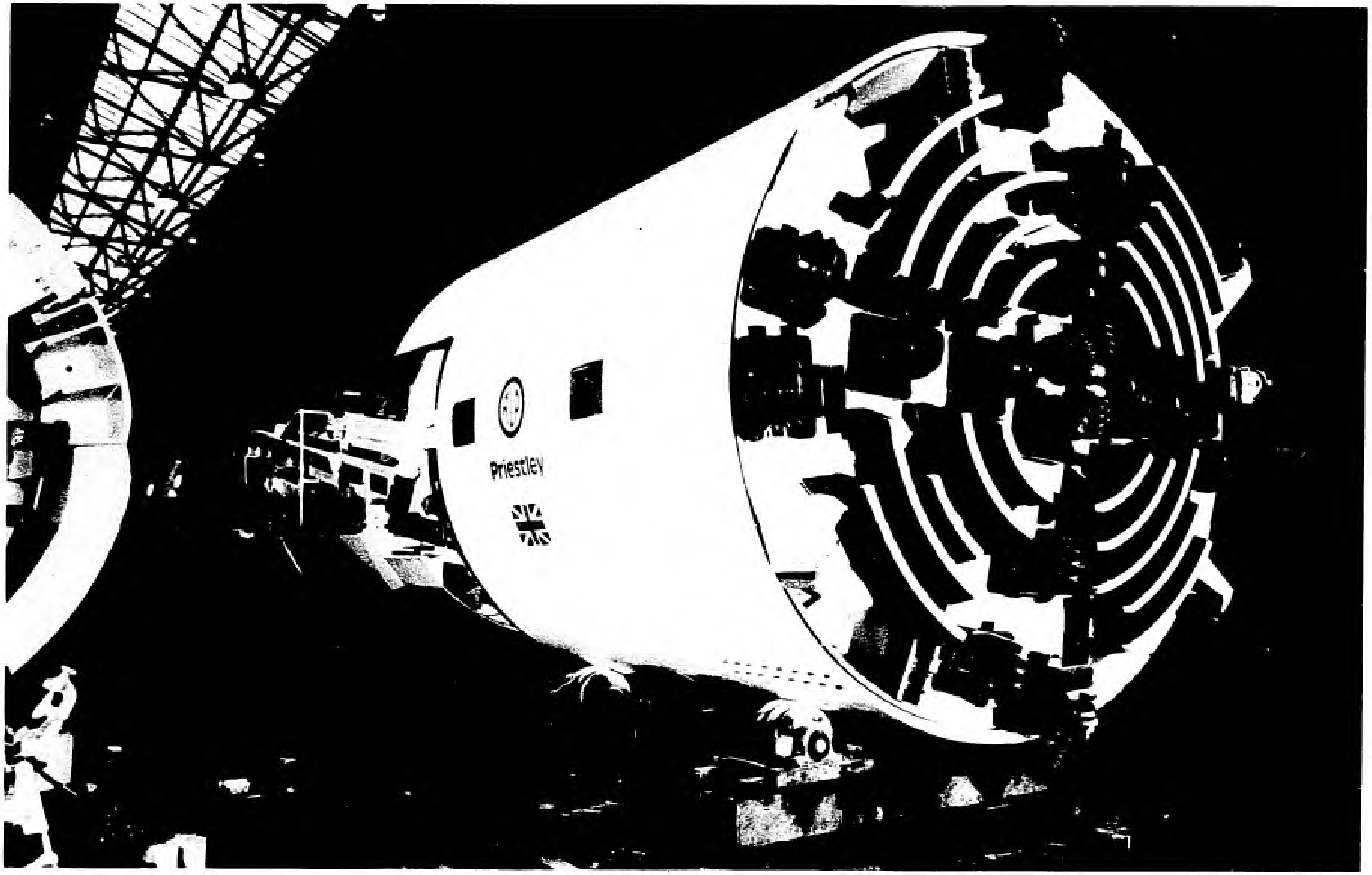


Figure 12. Shielded full-face tunnel boring machine for rock tunnels; note face construction details with concentric ring grill bars to prevent blocks from sliding out and jamming in muck buckets or between cutter discs (courtesy of Robert Priestly Ltd.)

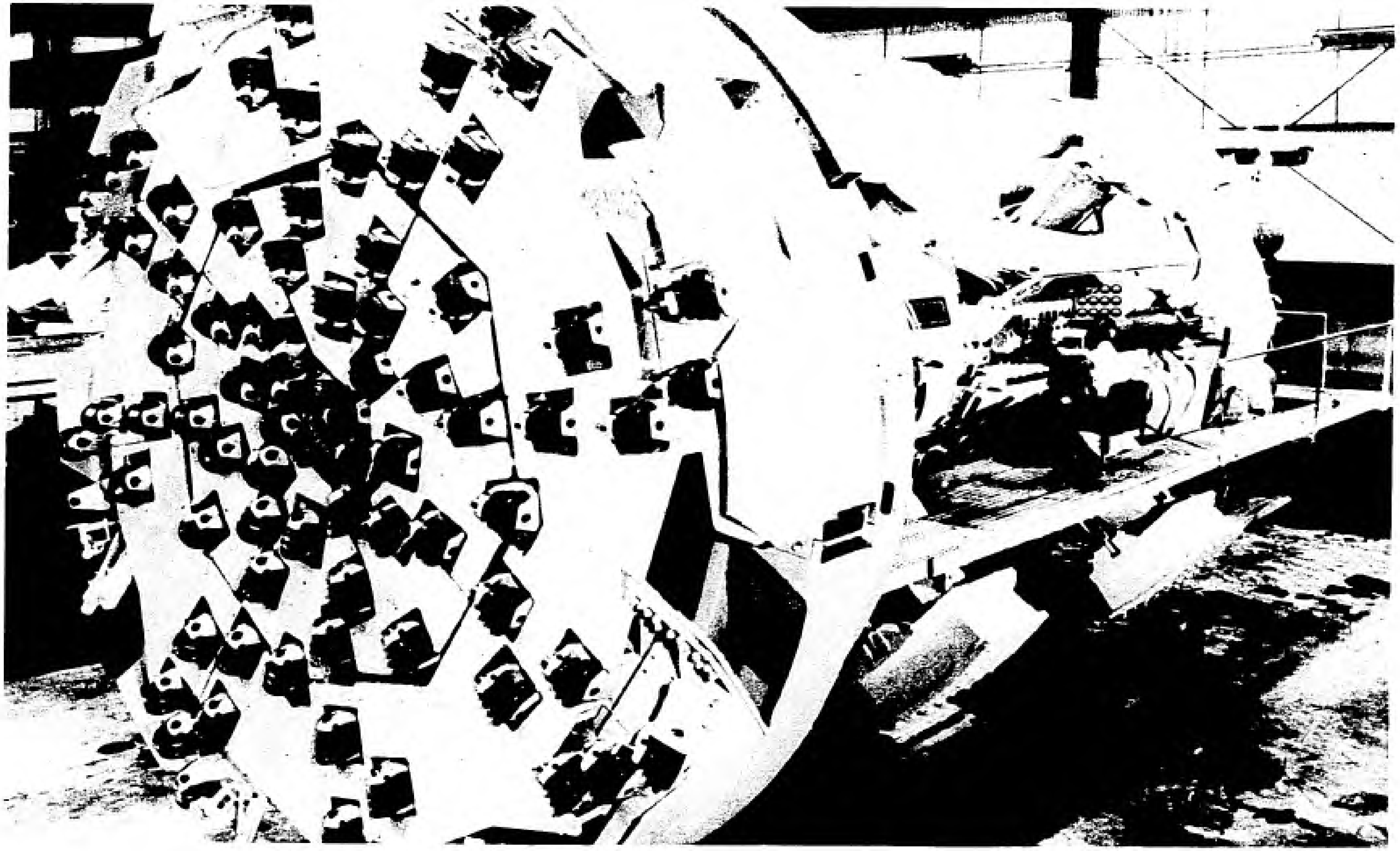


Figure 13. Full-face tunnel boring machine for deep rock tunnels; note that cutter discs are recessed in false face to limit free space between rock face and cutter head, and thereby prevent rock blocks from sliding out and jamming machine. Note also the lack of a telescopic shield, allowing early placement of support and minimizing problems from squeezing ground (courtesy of Robbins Co.)

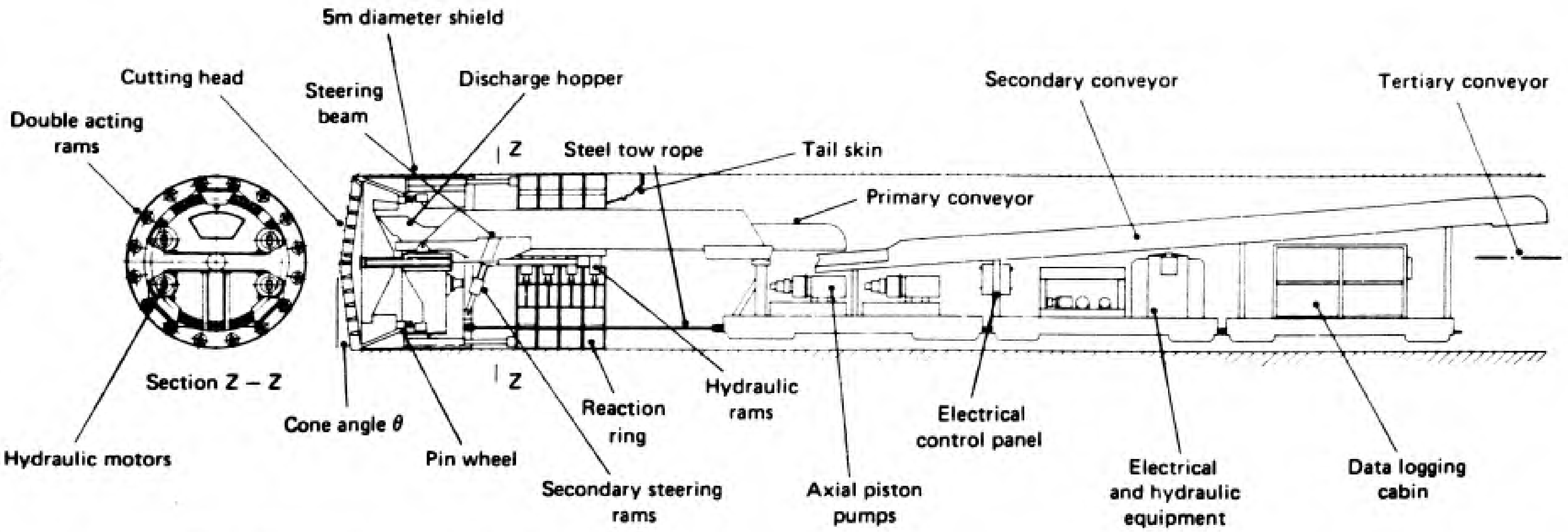


Figure 14. General layout of shield TBM employed in soft ground (after Hignett and O'Reilly, 1977)

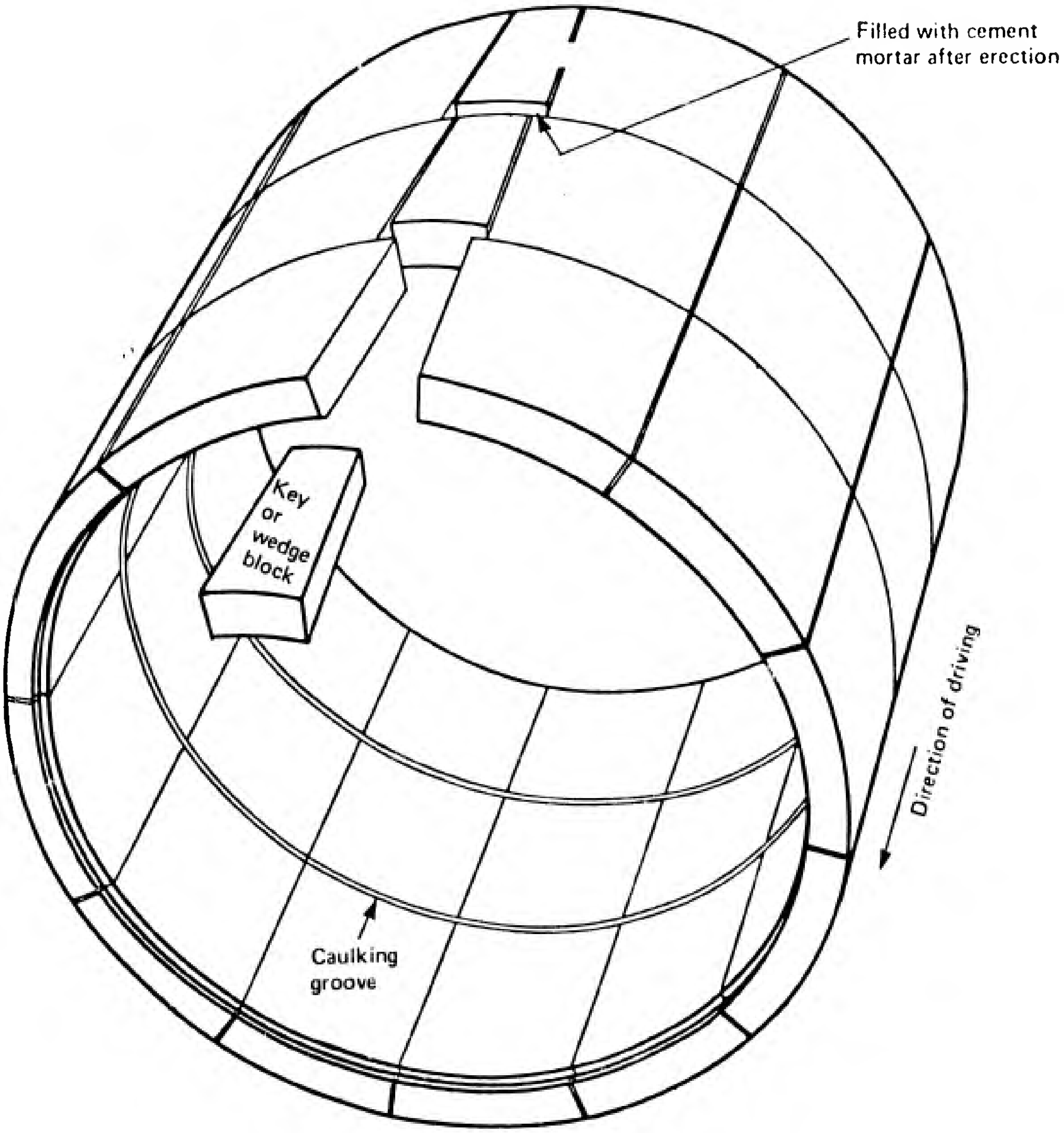


Figure 15. Wedge block expanded concrete segmental lining (from Craig and Wood, 1978)

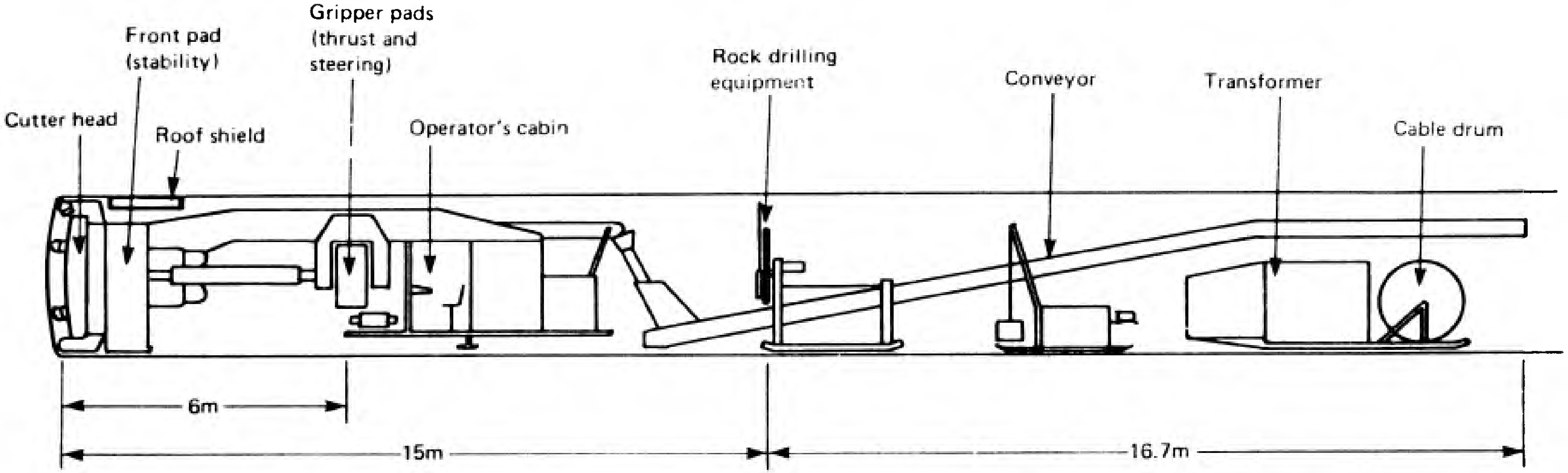


Figure 16. Schematic of tunneling machine (Robbins model 123-133)

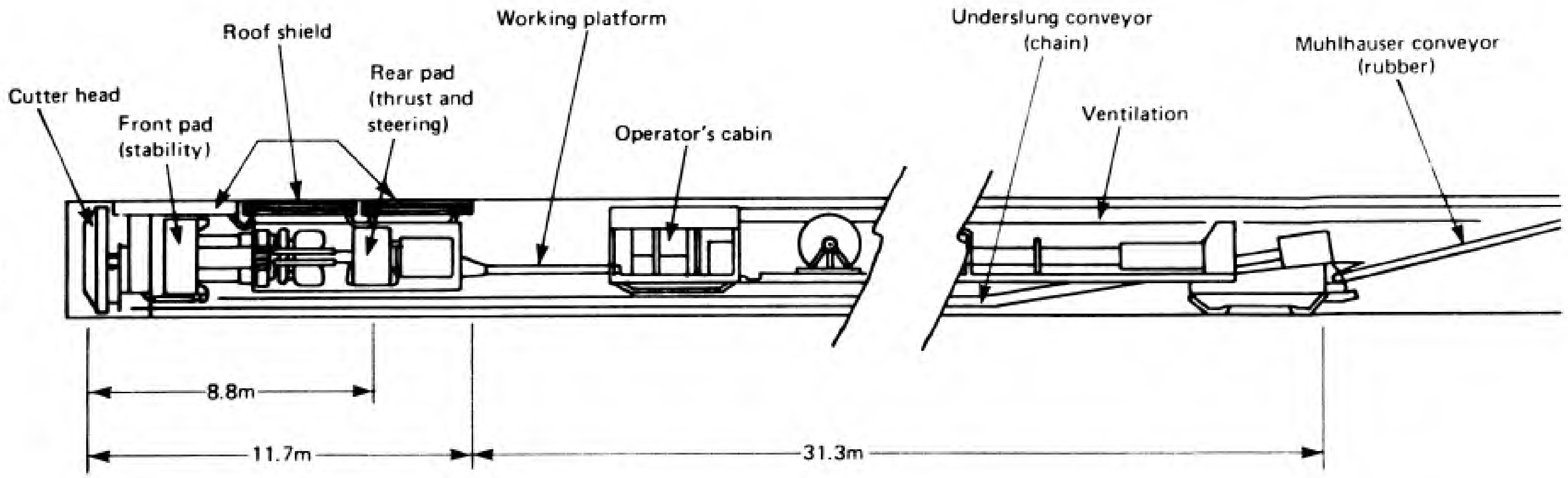


Figure 17. Schematic of tunneling machine (Demag TVM 34-38)

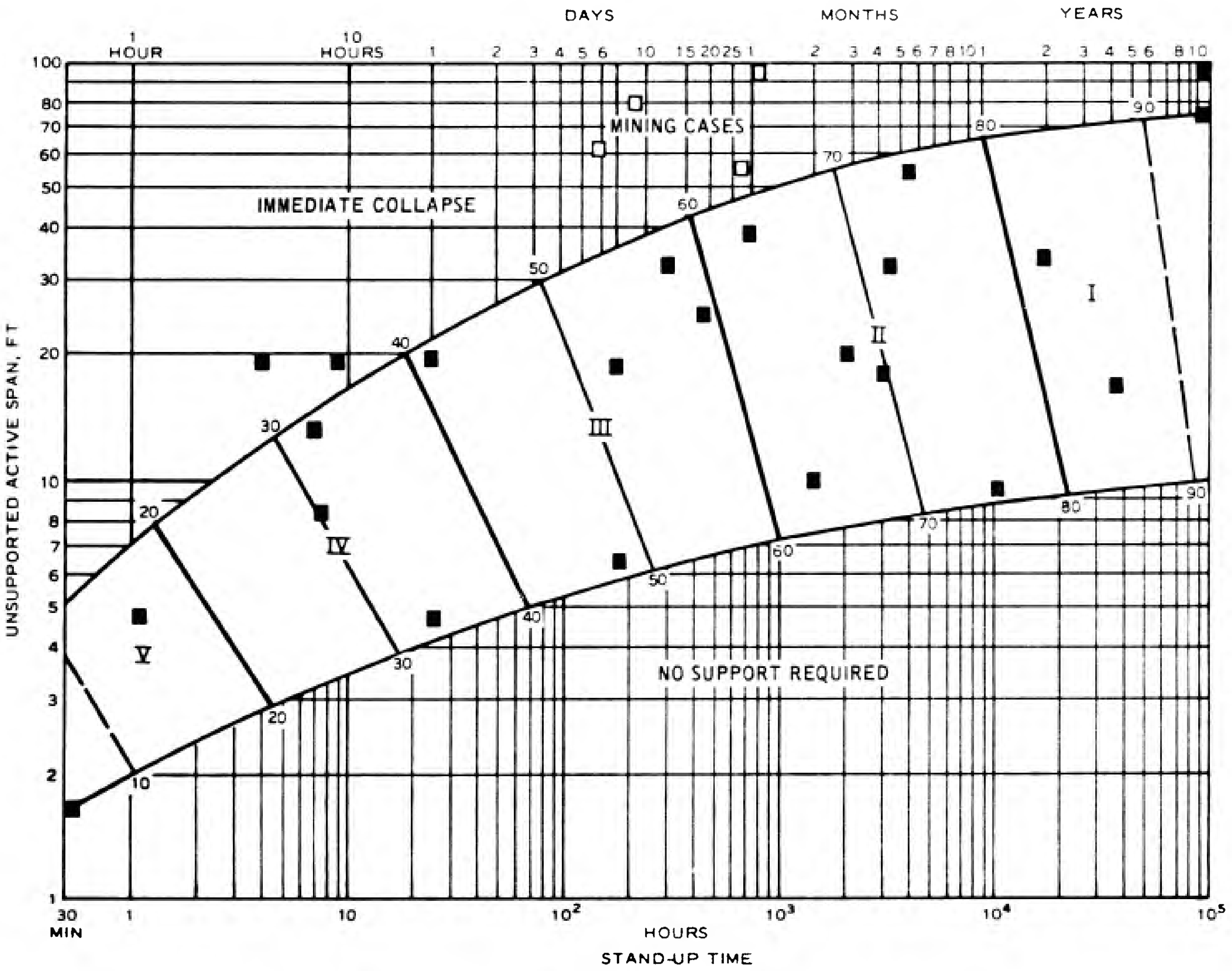
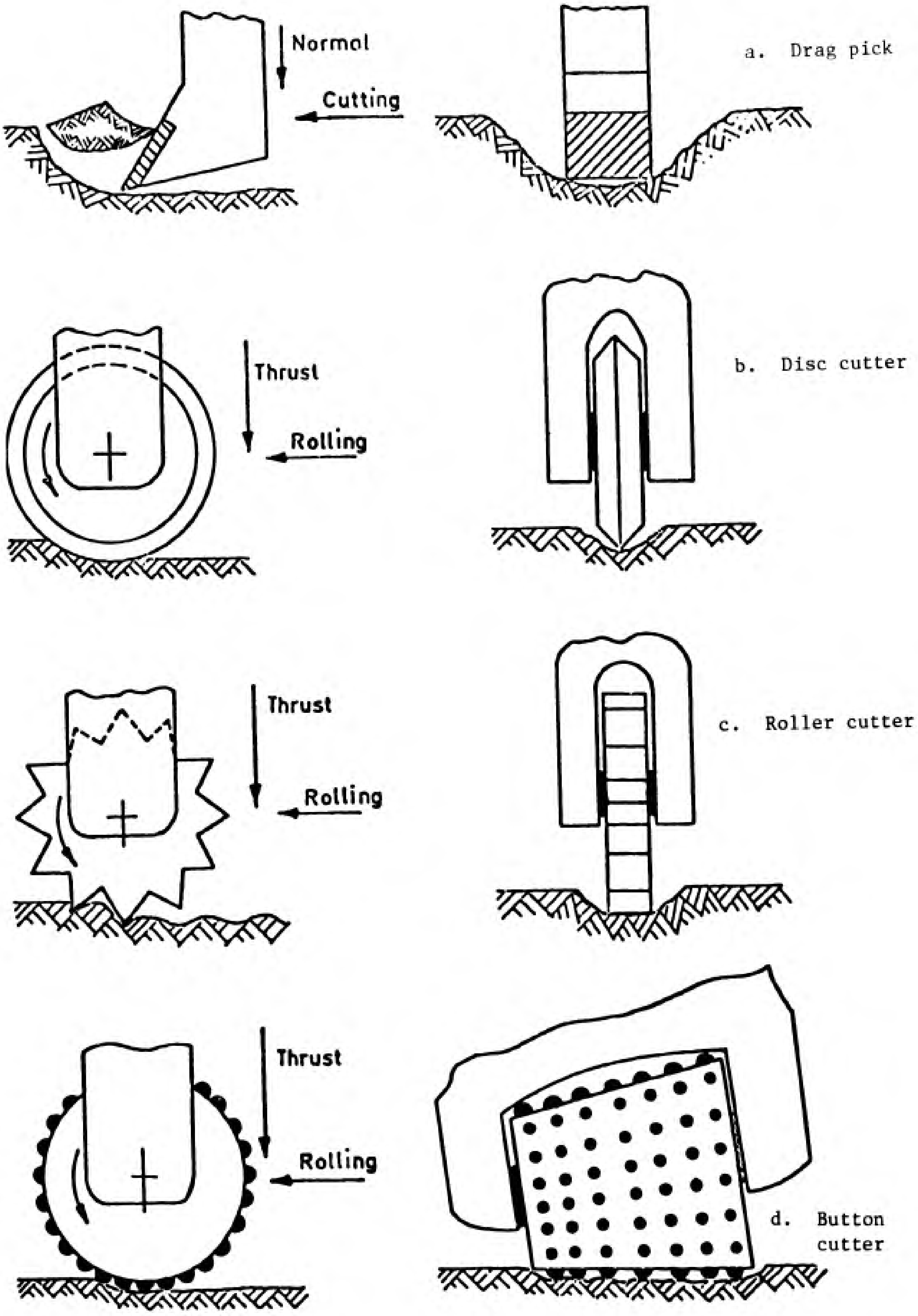


Figure 18. Geomechanics classification, output of stand-up time versus unsupported span. For description of rock mass categories I-V, see Bieniawski (1979)



a. Drag pick

b. Disc cutter

c. Roller cutter

d. Button cutter

Figure 19. General types of cutters

F_N = Normal force
F_C = Cutting force
F_S = Sideways/lateral force
W = Pick width
S = Spacing
D = Depth of cut
α° = Pick rake angle
δ° = Break out angle

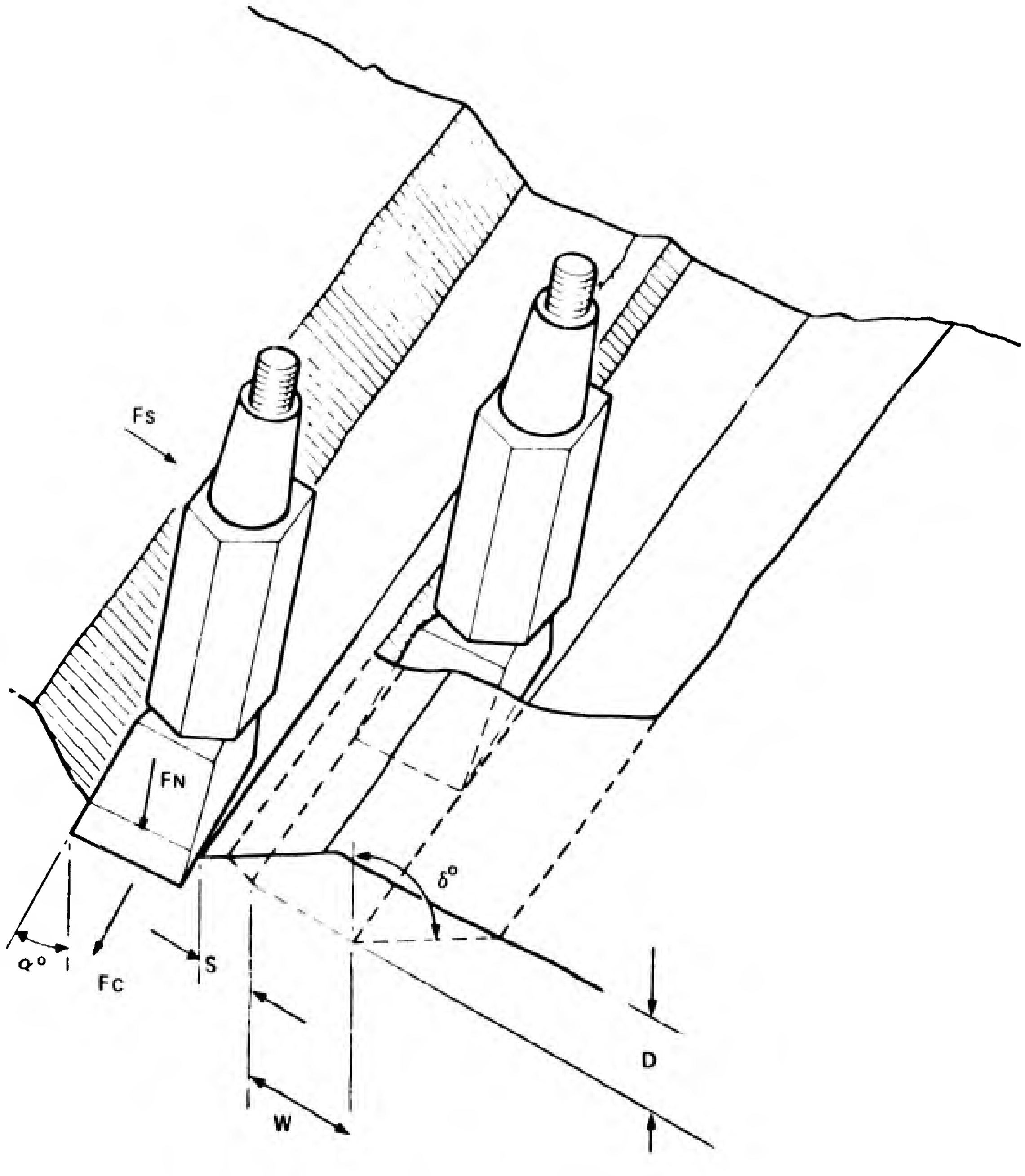


Figure 20. Terminology and geometry of drag pick cutting (after Hignett and O'Reilly, 1977)

F_N = Normal force
F_R = Rolling force
F_S = Sideways/lateral force
W = Disc width
S = Spacing
P = Penetration
$2\beta^\circ$ = Disc edge angle
δ° = Break out angle

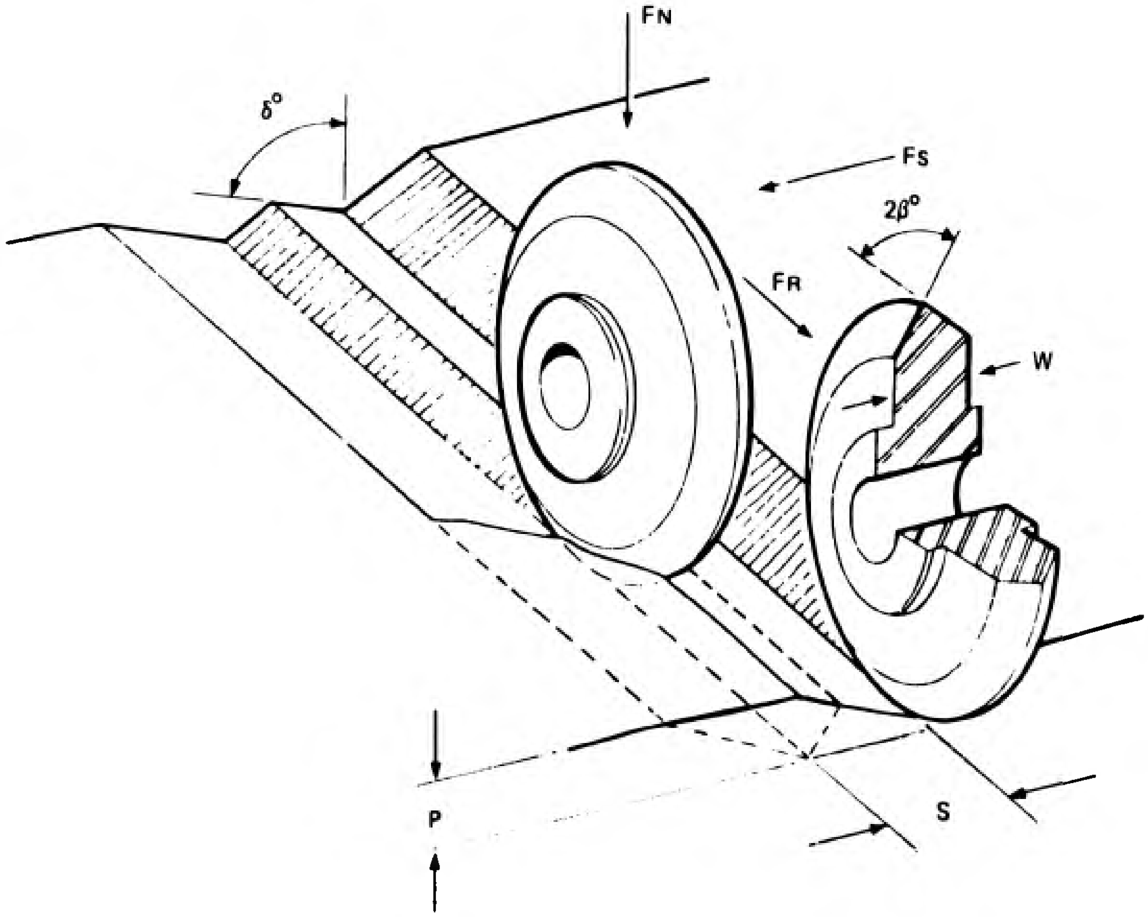


Figure 21. Terminology and geometry of disc cutting (after Hignett and O'Reilly, 1977)

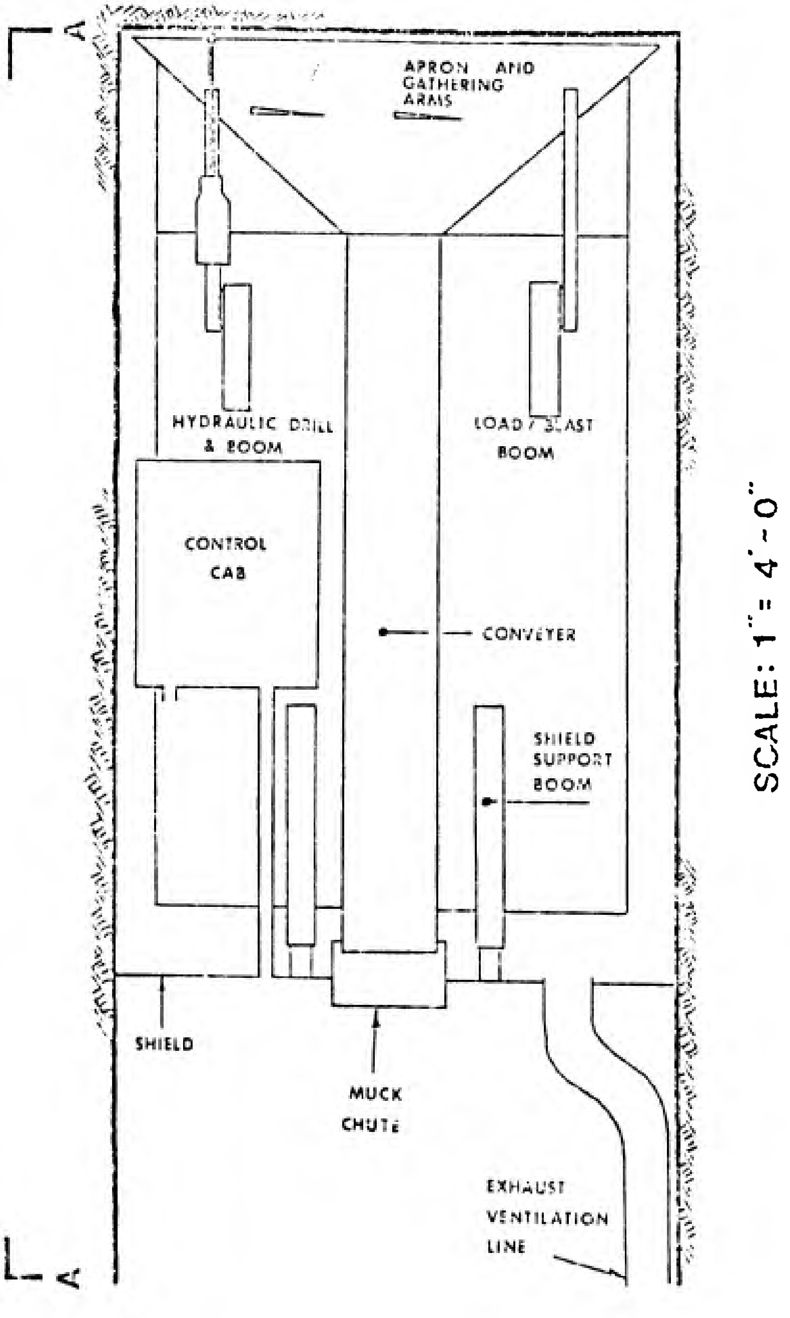


Figure 22. Plan view of proposed automated drill and blast system (after Clark, Ashcom, and Hanna, 1980)

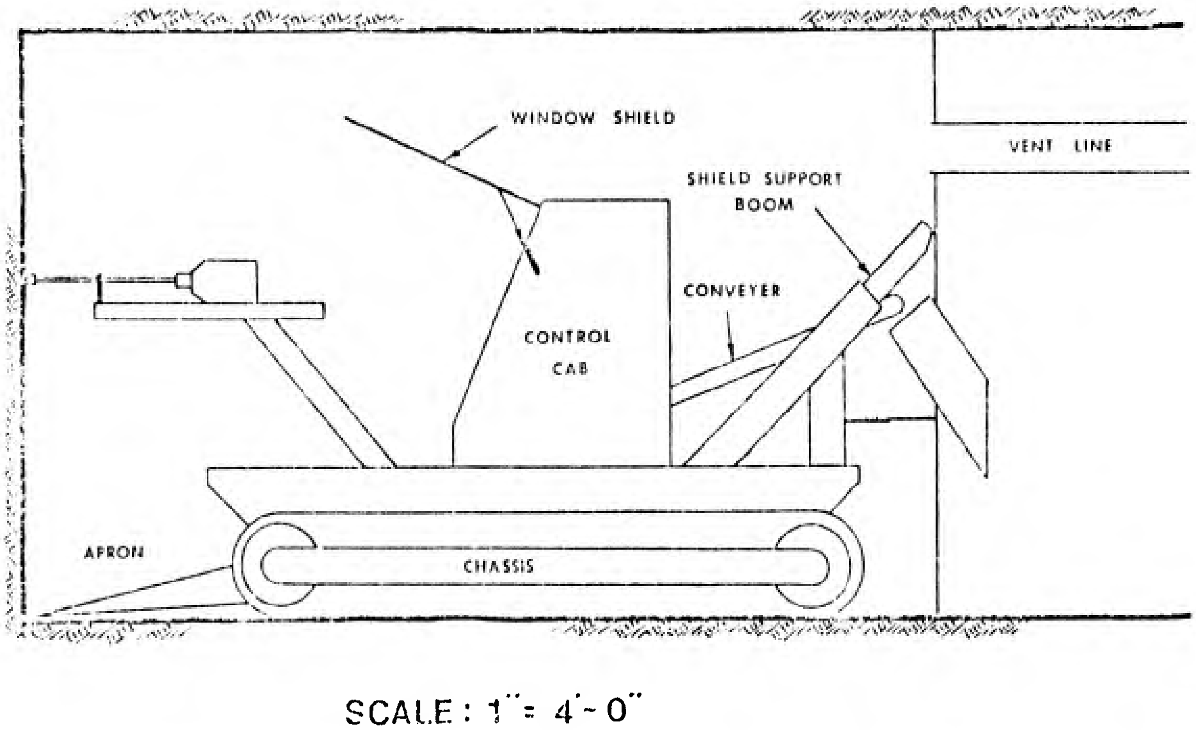


Figure 23. Section view of proposed automated drill and blast system (after Clark, Ashcom, and Hanna, 1980)

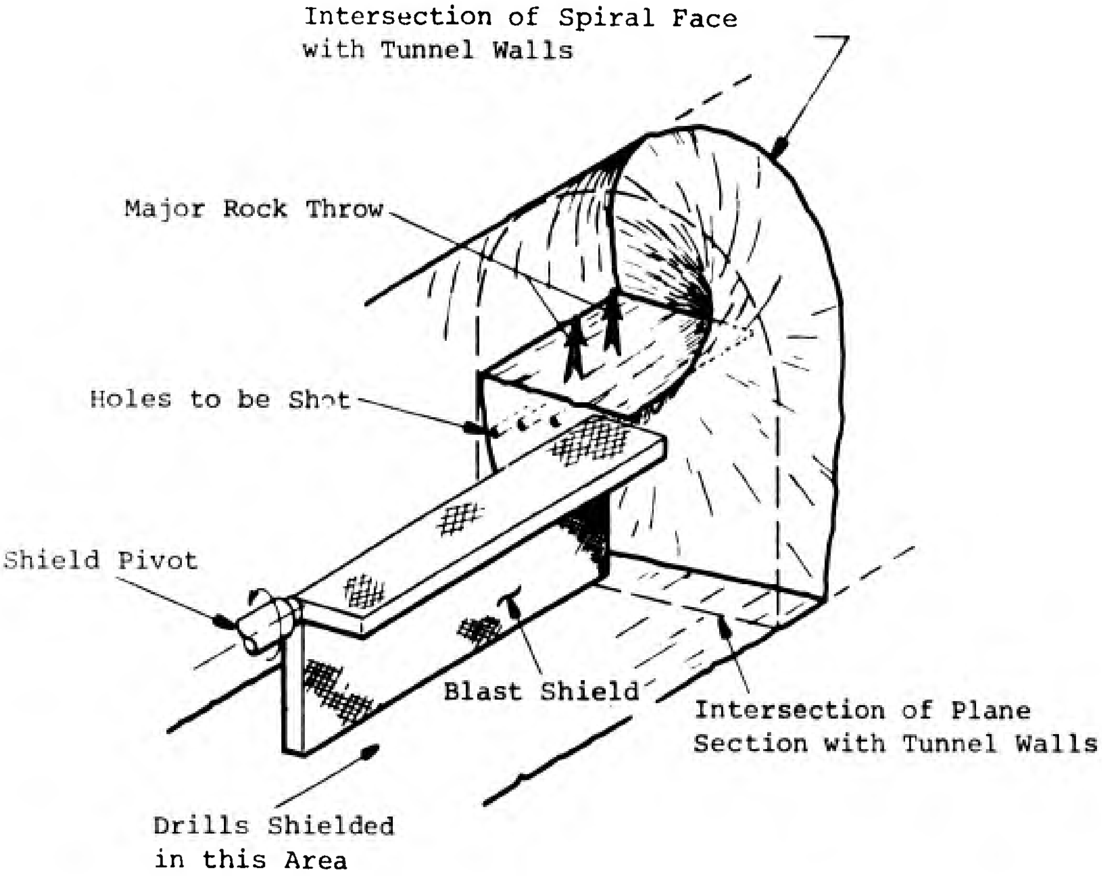


Figure 24. Schematic of spiral drill and blast concept (after Peterson, Fisk, and Lunquist, 1979)

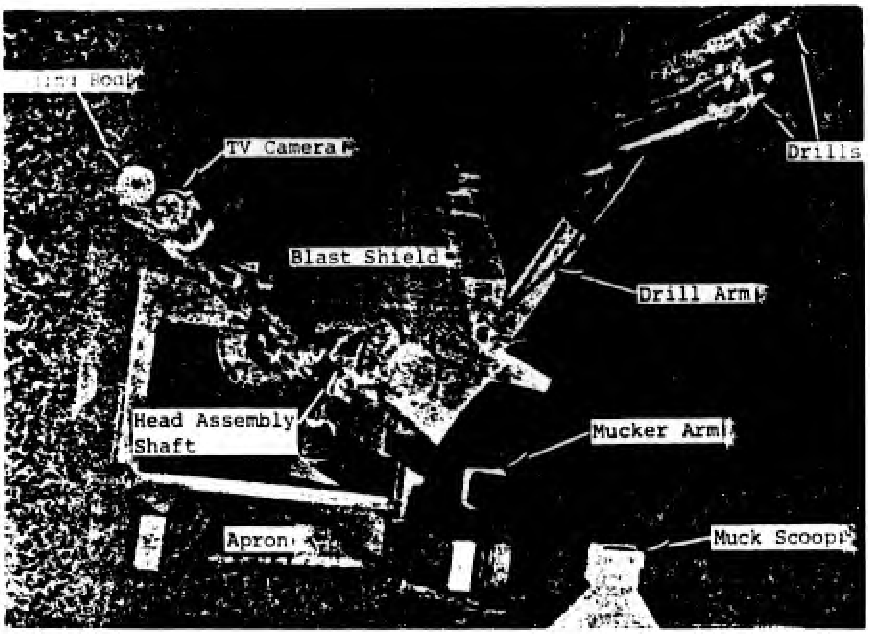


Figure 25. Front view of spiral drill and blast machine (after Peterson, Fisk, and Lundquist, 1979)

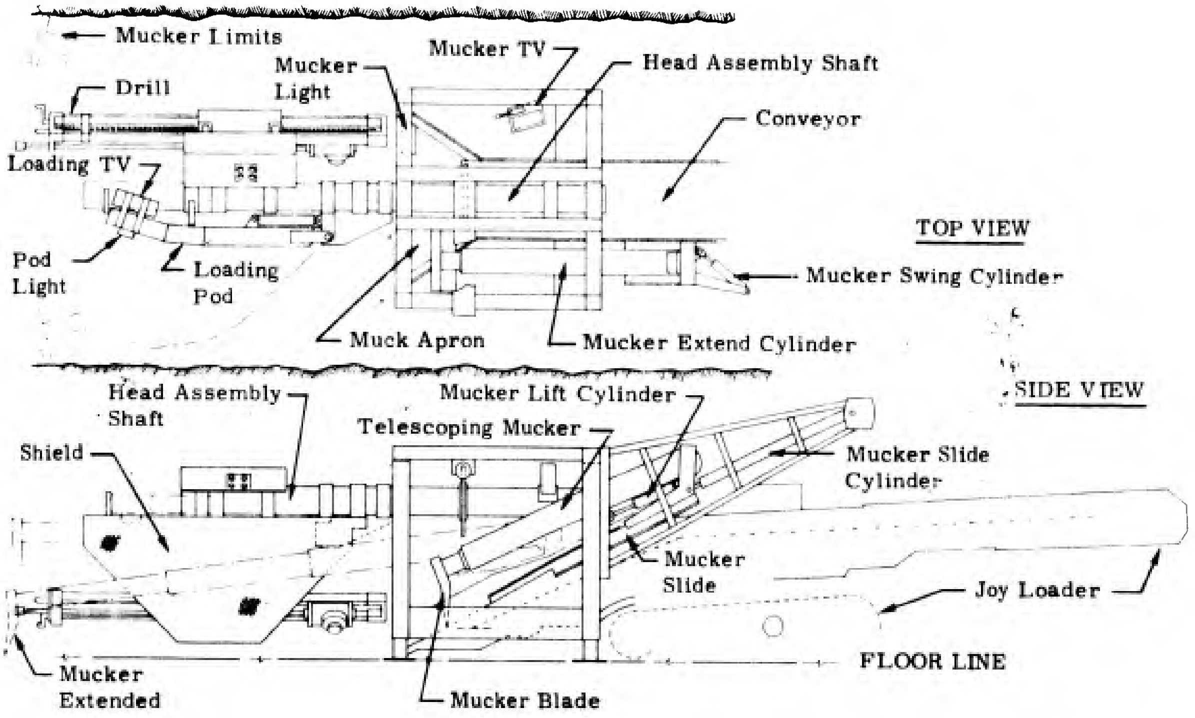
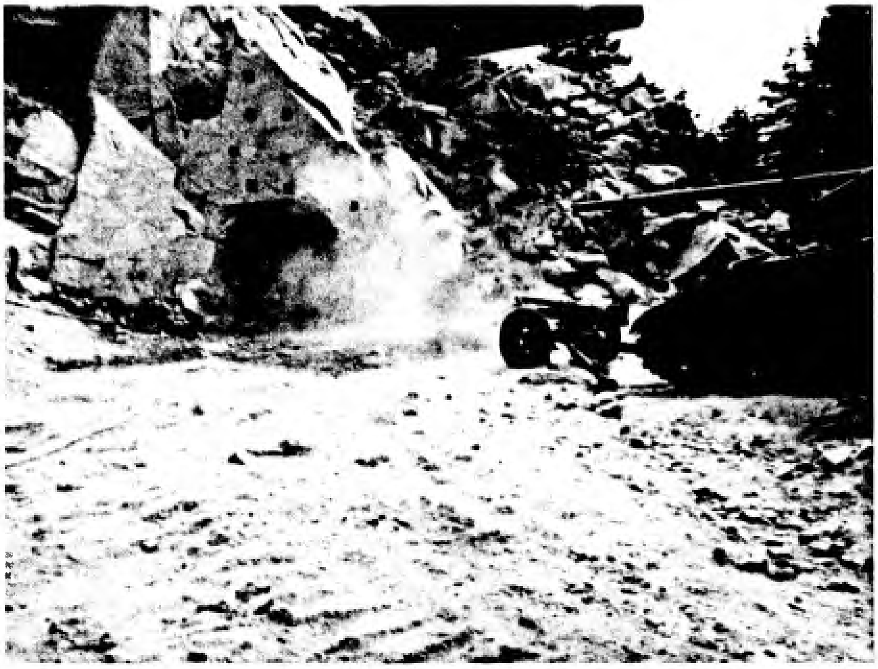


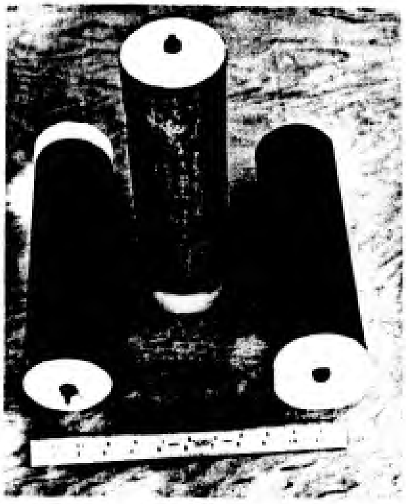
Figure 26. Plan and section views of spiral drill and blast and mucking system (after Peterson, Fisk, and Lundquist, 1979)

a. 90-mm and 57-mm guns

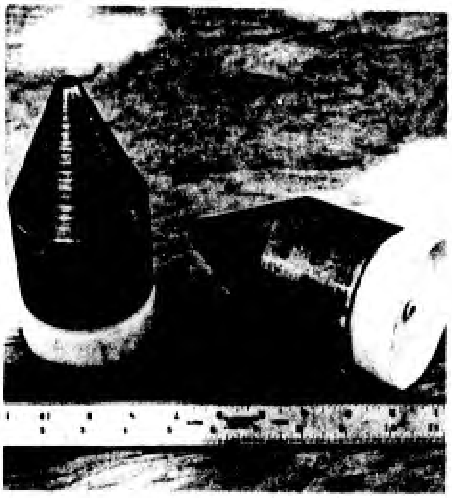


b. 57-mm gun firing into the tunnel

Figure 27. View of the 57- and 90-mm field guns (after Watson and Lundquist, 1974)



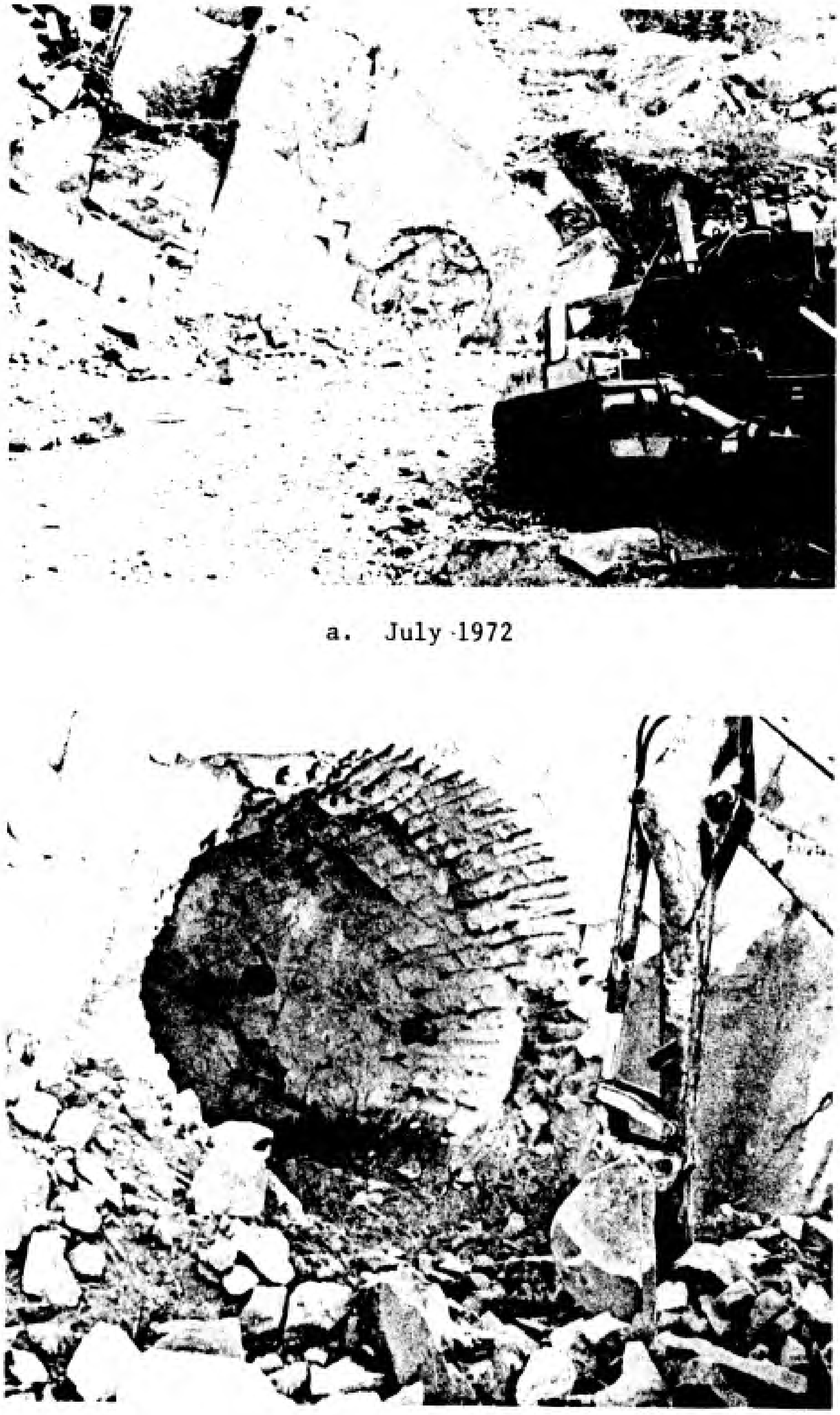
a. 90-mm concrete projectiles



b. 90-mm pointed steel projectiles

c. 57-mm and 90-mm projectiles

Figure 28. Projectiles used on project REAM (after Watson and Lundquist, 1974)

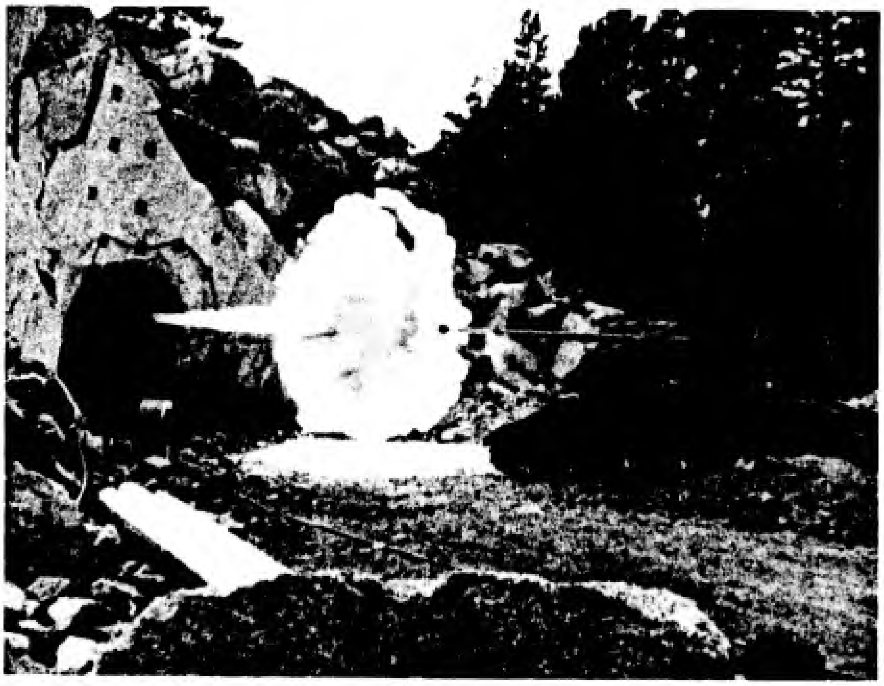


a. July 1972

b. October 1972

Figure 29. Field gun in firing position outside of portal (a) and viewing of excavated tunnel (b) (after Watson and Lundquist, 1974)

a. 90-mm silenced cannon fireball



b. 90-mm unsilenced cannon fireball

Figure 30. Outside view of firing the 90-mm field gun

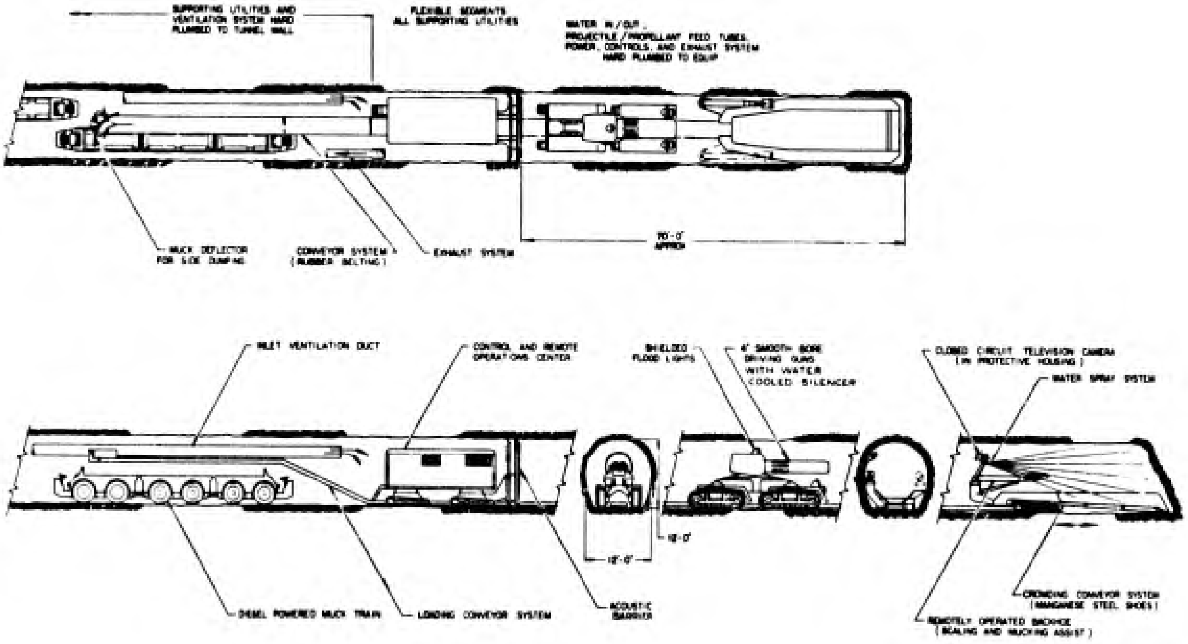


Figure 31. Conceptualization of an integrated REAM system for tunneling (after Watson and Lundquist, 1974)

Figure 32. View of TBM cutterhead with water jet manifold (courtesy of Flow Industries)

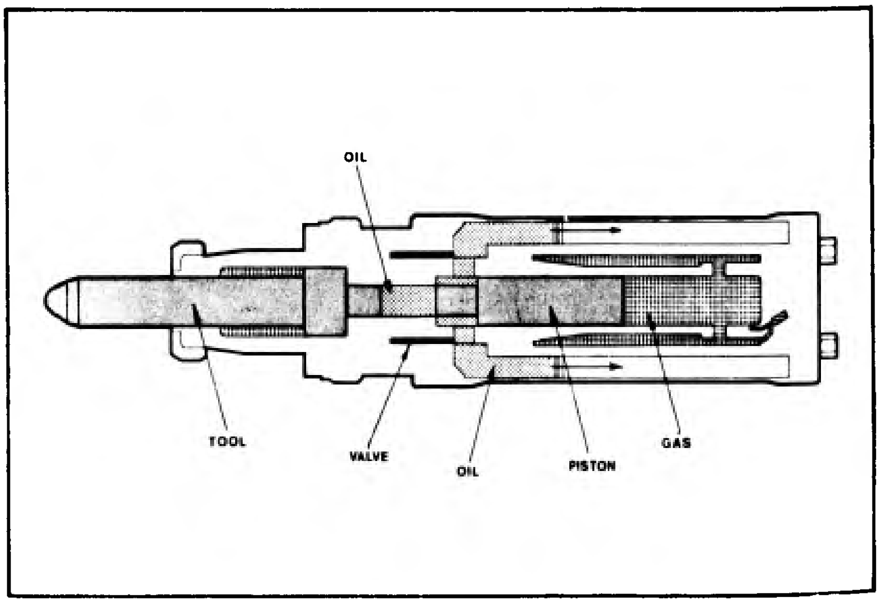


Figure 33. Hydraulic impactor with fluid coupling
(after Wayment and Grantmyre, 1976)

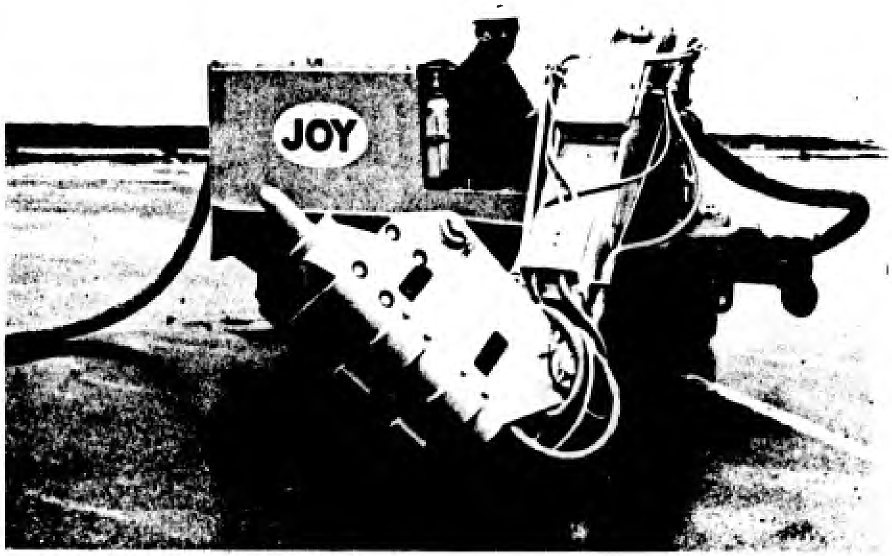
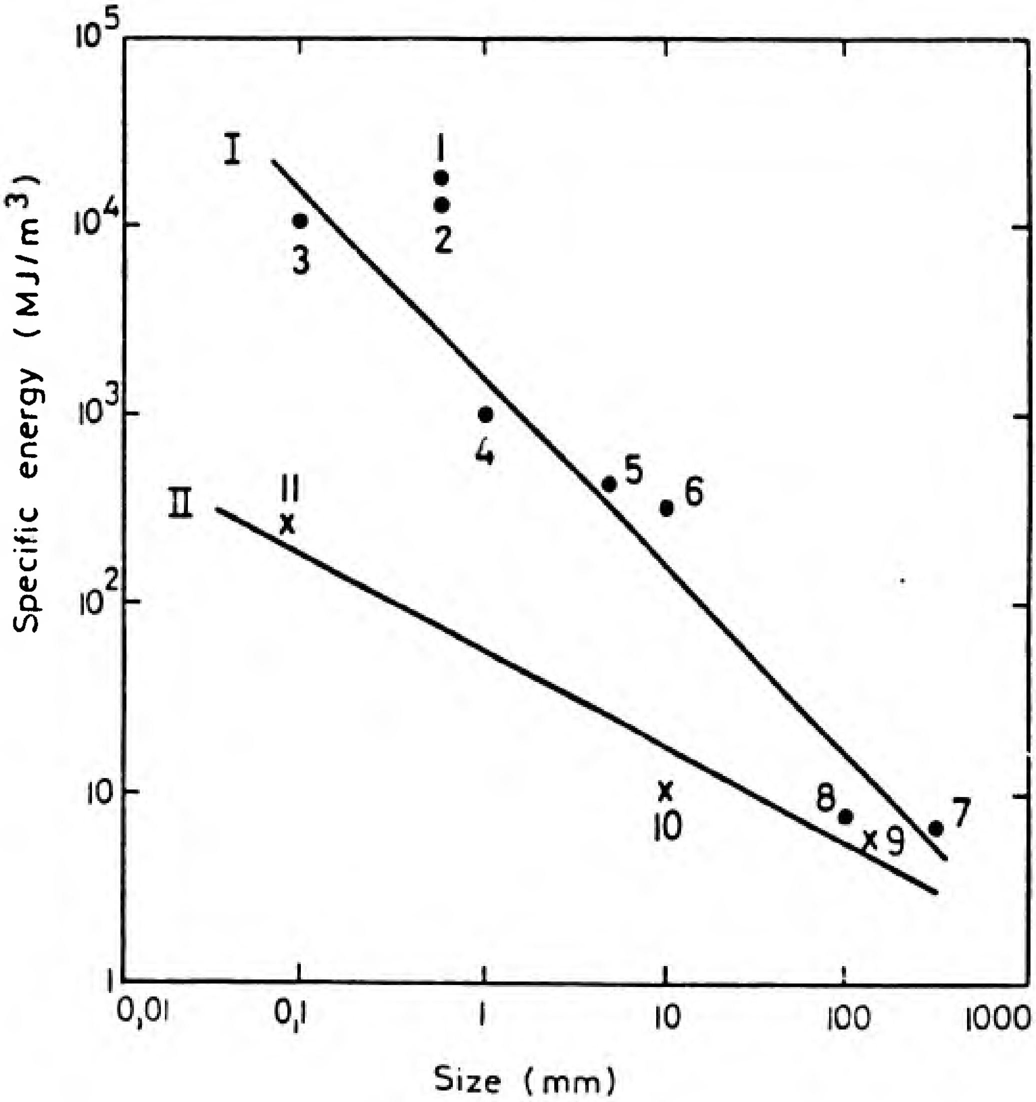
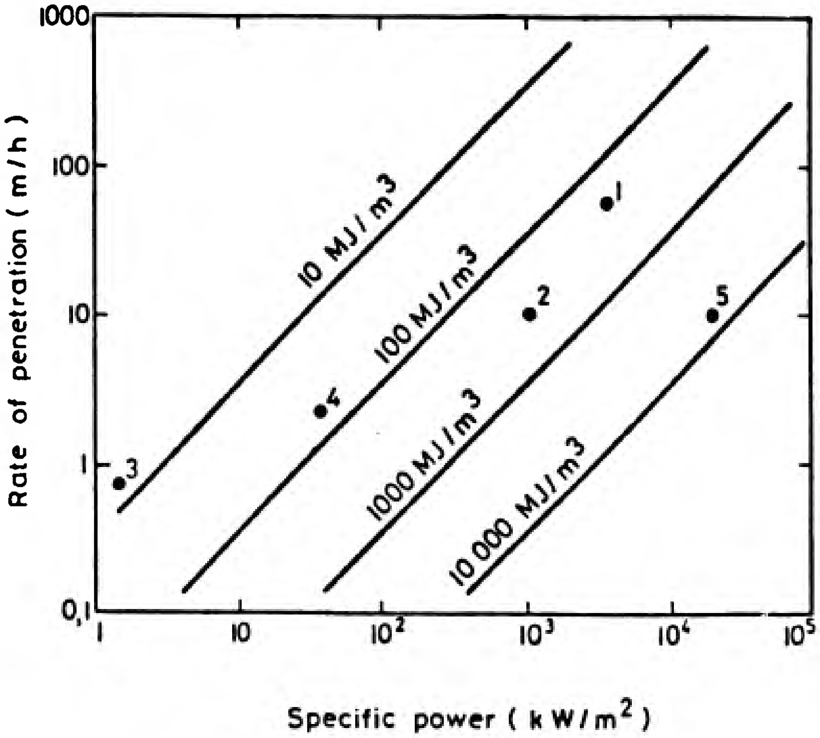


Figure 34. Joy underground miner with a Model 206 HEFTI hammer (after Wayment and Grantmyre, 1976)



1 = Jet-piercing; 2 = erosion drill; 3 = diamond cutting; 4 = percussive drilling; 5 = drag-bit cutting; 6 = roller bit boring; 7 = impact-driven wedge; 8 = explosives; 9 = jaw-crusher; 10 = gyratory crusher; and 11 = milling

Figure 35. Graph of specific energy versus particle size; I = excavation and II = comminution (after Cook and Harvey, 1974)



1 = Percussive drills (small); 2 = rotary drills; 3 = drill-and-blast tunneling; 4 = raise- and tunnel-boxing machines; 5 = novel methods

Figure 36. Comparisons of standard and novel excavation methods in terms of penetration rates, specific power, and specific energies (after Cook and Harvey, 1974)

PART III: SHAFT CONSTRUCTION METHODS AND EQUIPMENT

192. Methods and equipment used to construct deep shafts in rock are discussed in this section. These methods include conventional shaft sinking, inclinded shaft sinking, impactor shaft sinking, conventional shaft raising, raise boring, blind hole raise boring, large-diameter drilling, reaming, and blind shaft boring. In addition, shaft shape considerations and shaft collaring are discussed.

Shaft Shape Considerations

193. Shafts are complex structures whose design requires technical knowledge and practical experience. Aside from the traditional design considerations, such as shaft location, surface plant, hoisting capacity, ventilation, shaft shape is primary to planning and design. After construction begins, the shape of the shaft cannot be readily modified. Consequently, shape is a relatively rigid constraint on the conceptual design process and proposed end use.

194. Basically, only two shapes of shafts are usually considered, rectangular and circular. The elliptical and ovaloidal shapes have been utilized, but they are somewhat incompatible with modern excavation techniques and service equipment. However, in many cases they are preferable from the standpoint of stress concentrations in the surrounding wall rock.

195. The decision on shaft shape is usually based on previous experience in a given area, with major consideration given to the proposed service requirements. The basic shapes are also extremely sensitive to applied rock loads.

Shaft Collaring

196. The shaft collar is that portion of the shaft extending from the surface to the bedrock. Collars are required for all shafts because the soil overburden requires special excavation and support techniques. This, in turn, requires different equipment and sometimes even different crews than are used for the shaft itself. Only after completion of the collar can the shaft sinking equipment be installed and the shaft construction begun. Because of

the similarity between shaft collars and deep foundations, and because of the advances that have been made in the technology of deep foundation construction, methods from both industries are discussed.

197. Geologic conditions of the unconsolidated overburden affect the design and construction methods, the cost of the collar, and how long it takes to construct the collar. The soils overlying the rock formations vary from thick to thin, cohesive to noncohesive, and from dry to containing almost unmanageable quantitites of water.

198. The construction techniques available for constructing shaft collars are:

a. Conventional construction.
b. Sheet pile ring wall.
c. Incomplete ring of drilled piers.
d. Slurry trench wall.
e. Large-diameter drilled pier.

199. Only the conventional method and the drilled shaft method are known to have been used on an inclined shaft, and even then the excavation and lining systems are very specialized. Ventilation, power, and communications are easily handled because of the relatively shallow depth. The large-diameter drilled pier is the least expensive if the soil is cohesive, and collaring costs generally increase as the soil becomes less cohesive and the diameter and depth increase. The techniques can be extended in diameter and depth by developing sheet pile that can be driven deeper, larger auger systems, equipment to excavate slurry trenches deeper, and large-diameter drills adaptable to collar excavation.

Conventional construction

200. Conventional construction uses a side-slope excavation cutback and a sheet pile or liner plate ground support system. Under good soil conditions, the upper portion of the excavation (5-10 ft) can be scooped or dozed. The remainder is excavated by clamshell. Liner plates bolted together support the walls. After the inner forms and reinforcing steel are installed, the concrete collar is cast and backfilled. Figure 37 is a sketch of a cast in-place shaft collar inside a steel liner plate.

201. Where the soil sloughs or where there is considerable water, grouting or freezing is necessary. These control measures appreciably increase costs and construction time. Advantages of the use of steel liner

plates are: (a) proven technique with crews and equipment available, (b) applicable to a wide range of ground conditions, (c) needs little construction area, (d) liner plates become outer form and can stay to aid support, (e) two men with no special equipment can handle the liner plates, (f) prefabricated liner forms can be easily installed because the collar is completely excavated before lining, and (g) there is no limit to depth. Disadvantages are: (a) large water inflows can cause difficulties; (b) hand trimming and some backfilling are labor-intensive but necessary to support outer forms during concreting; (c) liner plates cannot be recovered, which increases costs; and (d) liners can only take circumferential compression which may necessitate internal bracing.

Sheet pile ring wall

202. The oldest and simplest technique for supporting loose and soft water-bearing formations is the driving of interlocking sheet piling around the outside perimeter of the collar. The soil is excavated and then the collar is cast in-place between an inner form and the sheet pile. Reinforcement can be prefabricated on the surface and lowered between the forms such as shown in Figure 38. Advantages of the use of sheet pile ring walls are: (a) proven technique with crews and equipment available, (b) rapid installation in unstable ground with appreciable groundwater because they are watertight, (c) small work area required, and (d) sheet pile is used as the outer form but can be removed if not needed for additional support. Disadvantages are: (a) soils must be soft with no cobbles or boulders, (b) depth is limited to 50 ft with most being less than 35 ft, and (c) unequal radial forces may require internal bracing.

Incomplete ring of drilled piers

203. Another faster collaring method uses small-diameter piers spaced 2 or 3 diam apart around the collar periphery. Reinforcement cages are lowered into drilled holes and the piers are cast in-place. The collar is excavated by any appropriate means, and the material between the piers is retained by the bridging action of the soils. An inner form, or casing, and the piers are used in the casting of the collar, with the piers being incorporated into the collar if desired. Because of the need for the bridging action, this technique is only practical under certain soil conditions and when there is no groundwater. Figure 39 diagrams the drilled pier ring-wall method. Advantages are: (a) proven technique with crews and equipment available, (b) rapid,

(c) inexpensive for cohesive soils with little groundwater, (d) small construction area required, (e) the pier-supported ground can act as the backform, and (f) the piers can add to the collar strength. Disadvantages are: (a) limited to cohesive soils or soft rock with minimal groundwater, (b) maximum depth is 30 to 50 ft, and (c) uneven radial loading may require internal bracing.

Slurry trench wall

204. The slurry trench wall, shown in Figure 40, is a method good in almost any soil condition. A trench is excavated, generally in segments, around the periphery of the collar to the desired wall thickness. Mud slurries support the trench walls during excavation. Concrete is placed under the mud by the tremie process. The material inside the collar can be removed by drill or clamshell as shown in Figure 41. Advantages are: (a) no internal bracing required, (b) bentonite slurry controls groundwater, (c) applicable to any soil or rock type, (d) small construction area, and (e) any shape can be constructed. Disadvantages are: (a) requires specialized crews and equipment, and (b) because concrete pours are not continuous, cold joints between pours can leak groundwater.

Large-diameter drilled pier

205. The large-diameter drilled pier is the fastest and least costly method and it has been used extensively at the Nevada Test Site (NTS) in diameters up to about 12 ft. This method is shown in Figure 42. At NTS, an auger was suspended from a crane and driven by a Kelly. The cuttings are removed by removing the muckladen auger. Collars 75 to 100 ft deep are possible if the soil can stand unsupported. Sloughing or overbreaks only increase the wall thickness. Advantages are: (a) very rapid excavation in cohesive soils, (b) small work area, (c) prefabricated forms can be rapidly lowered into the hole, and (d) rapid excavation and installation of the forms reduces the time the hole stands open, thus reducing the need for temporary support. Disadvantages are: (a) cannot be used in noncohesive soils because there is no temporary support; (b) the maximum diameter at this time is about 12 ft, but could be increased; and (c) bentonite slurries cannot be used while the auger is being used.

206. All of the collaring methods discussed in this section are compatible with the mechanized types of shaft sinking. Although some of the methods can be adapted to different shapes and designs, for this study, all were considered circular.

Conventional (Drill and Blast) Shaft Sinking

207. The conventional method is so named because it is the standard method for sinking shafts throughout the world and has been used since the earliest days of underground mining. While the basic principles remain unchanged, improvements through mechanization and more efficient blasting techniques have increased productivity and reduced hazards to miners. Most shafts have been sunk by the conventional method.

208. Conventional shafts are sunk by repeating a cycle of drilling, blasting, removing muck, and lining the shaft with concrete or installing timber or other types of ground support. Typically, the required major pieces of equipment are rock drills (normally pneumatic), a hydraulically-operated clamshell-style muck loader, hoisting buckets, concrete forms, water pumps, and ventilation fans.

209. Shafts are normally sunk by contractors on a 3-shift-per-day, 7-day-per-week basis wherever possible. Projects done in-house by mining companies may not be as intensive due to a lack of qualified personnel, interference with mine production, or other reasons.

210. Productivity in a shaft project is a function of a number of related items, but the two most important are quality of personnel and ground conditions. In some areas, the pay scale for shaft miners is not significantly above that for other miners, and there is little incentive for qualified people to pursue these more difficult positions. The advance rate suffers as a result.

211. Independent contractors, in order to maintain a qualified crew, generally offer a greater financial incentive and usually are able to maintain a higher advance rate. A strong, knowledgeable supervisory staff is also essential.

212. It is possible to continue advancing a conventional shaft through severe ground and water conditions if the necessary items in the process (such as drill pattern, hole depth, and lining design) are changed to accommodate the adverse situations. Over the years, conventionally sunk shafts have been advanced through virtually all types of ground so there is a wealth of experience for the shaft sinkers to draw from when problems arise. Again, the capability of the crew is a key factor.

213. The average monthly rate of advance in this country varies from less than 70 to about 300 ft/month. A 6,100-ft-deep shaft project (18 ft diam, concrete lined) in North Idaho recently advanced 467 ft in one 31-day period (Crandall, Boyko, and Hemphell, 1981). In South Africa, where the conventional shaft sinking method is highly developed and safety rules are less stringent than in the United States, sinking rates over 1,200 ft/month have been achieved; these figures illustrate the tremendous variability in advance rates.

214. Drilling holes for blasting is normally done with pneumatic percussion drills, either by handheld sinker drills or mounted on a shaft drill jumbo. When sinking in relatively soft ground, rotary drills may be used. These jackhammers and drills range in weight from approximately 25 to 80 lb. The number of miners necessary to drill a round varies with the number of holes required, but typically a four- or five-man crew is adequate (Dames and Moore, 1977). Jumbos are frames upon which several drills may be mounted. The drills are mounted on hydraulically or pneumatically operated arms which may be positioned as needed to drill various patterns. In addition, one miner can operate two or three drills when using the shaft drill jumbo.

215. The shape and depth of the blast pattern are extremely important factors in the rate of shaft sinking. The shape of the pattern is determined by the ground condition and by the type of mucking equipment being used. The two basic patterns are the full-face and bench, as shown in Figure 43. With the full-face pattern, the entire bottom of the shaft is drilled and blasted in a single lift. In the bench pattern, half of the face is drilled and blasted in each shot.

216. The depth of the pattern is particularly important in achieving the maximum rate of advance. It is, however, limited by the size of the shaft, ground conditions, and overbreak produced. The depth varies from 5 ft in hard rock to 8 ft in sedimentary rock. After drilling the desired pattern, the rock must be blasted. Selection of the proper explosive is based upon several factors. These include rock hardness, drill pattern, and amount of water encountered. ANFO is preferred if there is no water. Because water commonly occurs in shaft sinking, cartridge-type explosives must be used. Explosive selection was discussed in more detail in Part II.

217. Mucking, or the pickup of broken rock from the face and dumping in a hoist bucket, is discussed in Part IV. Mechanical mucking equipment is

commonly hydraulic or air powered. Generally, the machines being used are either a form of clamshell suspended from the working platform or set into the wall, or are crawler-track, bucket-loader machines which move on the muck pile itself.

218. The hoisting system is perhaps the most critical component in conventional shaft excavation. In vertical shafts or steeply inclined slopes, the hoisting system is the sole means of access. Men and materials are raised and lowered by means of the hoist, and the broken rock is hoisted to the surface for disposal.

219. Platforms, work decks, or Galloway stages of various types support the miners while they line the shaft or install service lines. Single-deck platforms are used as a temporary stage while placing concrete and consist of several sections of wood or steel mats which are jacked against the concrete forms. After the concrete is placed, these platforms are freed and pulled from the shaft. More elaborate multideck Galloway stages remain in the shaft during the entire sinking operation (see Figure 44). In the United States, the most common type of stage consists of one to three decks. Because they remain in the shaft, they are fitted with wells to allow passage of muck buckets and supplies. The platforms are suspended by ropes mounted on hoists at the surface.

220. Ventilation in vertical and inclined shafts is essential for safe shaft operation. Common ventilation methods on United States shaft projects are discussed in Part VII.

221. Costs vary considerably with the following factors: ground conditions; crew experience; quality of supervision; quality of equipment; whether the miners are union miners and if so, the union that represents them; the shaft sinking procedures used; the rate at which capital equipment is amortized; and the amount of perceived risk. Costs vary from $2,000/ft to $6,000/ft. Two estimates taken from earlier studies and escalated to 1982 dollars are given below as examples.

20-ft-diam shaft estimates

222. The costs (1982) for sinking a 20-ft-diam, concrete-lined shaft, according to the U. S. Bureau of Mines' "Capital and Operating Cost Estimating System Handbook," are as follows:

Capital costs, per foot	$2,974
Operating costs, per foot	$2,818
Total cost, per foot	$5,792

22-ft-diam shaft estimate

223. The following hypothetical costs are taken from "Economic Forecast Analysis of the Blind Shaft Boring Machine," by the Paul Weir Company, and refer to a 22-ft finished inside diam shaft 1500 ft in depth. It assumes a rate of advance of 30 ft/week from 200 ft to 1,500 ft. The costs are escalated from April 1978 to 1982 dollars.

Description of Cost		Cost	Percent of Total Cost
Labor		2,897,000	53
Consumables (15 percent labor)		435,000	8
Site running (2.5 percent labor)		72,000	1
Freight		193,000	4
Equipment rental (hoists, compressors, etc.)		567,000	10
Installed equipment		196,000	4
	Subtotal	4,360,000	80
Direct Costs			
Concrete		401,000	7
Hanging rods		18,000	1
Formwork		15,000	1
Rebar		14,000	1
Mesh and bolts		7,000	1
Explosives		58,000	1
Drill steel		29,000	1
Spare parts		17,000	1
Pipelines		71,000	1
Cement and grout		25,000	1
Panning		157,000	3
	Subtotal	812,000	15
	TOTAL	5,172,000	
General and Administrative		259,000	
	TOTAL COST	5,431,000	
Profit - 15 percent of Total Cost		815,000	
	TOTAL PRICE	$6,246,000	

The total price for this shaft in 1982 dollars is $4,164/ft.

Inclined Shaft Sinking

224. The conventional tunneling method is applicable for driving declines with grades of 20 degrees or less. However, shaft sinking methods must be employed for driving declines with steeper grades since 20 degrees is the practical limit of conveyor haulage systems (Cummins, 1973). If the grade is over 20 degrees, the broken rock must be hoisted to the surface in skips.

225. The procedure for inclined shaft sinking is essentially the same as for vertical shaft sinking. The hoisting system is significantly different in inclined shafts; the skips ride on rails installed in the shaft.

226. A Cryderman mucker is normally used in inclined shafts because its clamshell bucket is mounted on a rigid boom that can be hydraulically supported and maneuvered. The bucket must be supported to keep it off the bottom of the shaft while the face is being mucked.

227. Depending on the angle of the shaft, rail-mounted jumbos, jacklegs, or sinker drills may be used to drill the rounds. Full-face or bench rounds may be used.

228. Ground support, water removal, and ventilation are handled much the same as in vertical shafts. These topics are discussed in Parts V, VI, and VII, respectively.

Impactor Shaft Sinker

229. The impactor was designed to sink circular or rectangular shafts through rock, replacing conventional drill and blast techniques. The broken muck is loaded into conventional muck buckets using a bucket mounted on a standard backhoe boom. Figures 45 and 46 show the system configuration. Figure 47 shows the impactor unit being tested.

230. The advantages of using impact breakage as a substitute for drilling and blasting in shaft sinking are listed below (Beus and Phillips, 1981):

a. No time lost in smoke clearing.
b. Overbreak is reduced.
c. The shaft wall is not fractured from blasting.
d. Shaft equipment lining forms are not exposed to the blast.
e. Spare parts can be stored on the galloway.
f. Simultaneous operations can be carried out.

g. Manpower can be reduced.

231. An impactor shaft sinker was constructed and tested by the U. S. Bureau of Mines with the objective of increasing shaft sinking rates by 25 percent, decreasing shaft sinking costs by 25 percent, and reducing worker's exposure to dust, blasting fumes, and sloughing rock (Geffen, et al., 1982). The cost advantages of the impactor have been estimated through an economic analysis for a 2000-ft shaft, because a recently built impactor has not yet sunk a shaft (Phillips, 1981):

	Cost saving using the breaker, percent	Increase in average sinking rate, percent
Rectangular shaft with a borehole	27.8	34
Rectangular shaft without borehole	8.7	2
Circular shaft with borehole	39.1	32
Circular shaft without borehole	34	16

232. Shaft sinking using the impact breaker requires essentially the same support equipment as does conventional sinking. This includes hoists, headframes, shaft conveyances, ventilation, power transmission, communications, and shaft dewatering.

233. Mobilization on site follows the same sequence as for conventional sinking, except that the machine is assembled as part of the galloway. The collar itself is sunk by standard methods until there is enough room to suspend the galloway and machine in the shaft, about 18 m. After installation of the headframe and the roping up of the galloway and muck hoists, sinking can commence.

234. The galloway is stationary during machine operation and is lowered in increments of 6 ft, 8 in.--a distance compatible with the boom reach. When operating, the galloway is restrained by eight positioning jacks providing lateral support.

235. While sinking, the machine should be able to excavate 20 ft in three shifts, based on an average rate achieved during field testing. This is followed by one shift to move the forms and pour the lining, and a shift to clean up and extend the service lines. For a 2,500-ft deep shaft, excavation and lining operations should proceed at an average of about 70 ft/week.

236. Mucking is accomplished with the backhoe on the impactor unit, which transfers the rock into conventional muck buckets for hoisting. Either a single- or double-drum hoist can be used, but it must be of sufficient capacity to minimize muck hoisting cycle time. The cycle of muck haulage is continuous during rock breaking and is halted only during shaft lining. It is possible to continue mucking during lining (since breaking is possible during the lining phase), although this approach would require that the concrete be delivered down the shaft by slick line instead of the muck buckets.

237. The concrete lining can be brought down to within a few feet of the bottom of the shaft, if required, and a 20-ft liner length poured using conventional techniques. This is convenient for many reasons, but shorter lengths may be poured if ground conditions require it and the forms are so designed. In addition, temporary wall support can be installed. The service pipes would normally be kept at a convenient height above the top deck of the galloway with additional pipe advanced in 20-ft lengths.

238. Perhaps the most important aspect of breaking rock, using impact tools as verified during the test excavations during the Bureau of Mines projects, is to have a free surface; such as a step or a bench to aid the formation of primary or secondary cracks. The systematic breaking and mucking sequence, envisioning the shaft bottom as adjoining pie-shaped segments, proved to be a productive mode of excavation. The actual rock breakage rate varied from 17 to 10 yd^3/hr, depending on rock characteristics and the skill of the operators. Rock type, joint frequency, and boom positioning time all greatly affect breakage rate. Rock strength and mechanical availability of the impactor, primary concerns during the initial stages of the project, do not now appear to be significant problems or limitations of shaft sinking using an impactor.

239. The impactor has been field-tested and its performance is dependent on the fracture characteristics of the rock. A recent commercial application was unsuccessful because the rock resisted cracking, apparently because of a toughness which may be predictable. Tests will be run to correlate toughness with impactor efficiency under a joint program between the contractor and the Bureau of Mines.

240. The impactor is not designed for sinking inclines more than a few degrees from the vertical.

Conventional (Drill and Blast) Shaft Raising

241. When there is access below the shaft site, a shaft can be raised by conventional drill and blast techniques. This method is labor-intensive and requires skilled shaft raise miners. Ventilation of the working area is difficult. After the raise is up about 150 ft, transporting materials becomes cumbersome and can slow the advance if upper levels are not available for access. This method is usually used for constructing ventilation or transportation shafts between mine levels, and is seldom used for long lifts.

242. In the case of a timbered shaft, the miner must first pry down any loose rock. Then he builds a platform on the uppermost set of timber to stand on for drilling the next round. After drilling is completed, additional timber is installed in lengths equal to the length of the drilled round. A sloping bulkhead directs the muck into a compartment used as a chute. The powder is then brought up to the face, and the holes are loaded and shot. Periodically, the air, water, and ventilation lines are extended up the raise close to the face.

243. As in raise boring, raising shafts does not require a mucking cycle. The muck will fall down in raises as flat as 40 degrees, but for raises under 40 degrees, muck generally requires some assistance for removal. Two methods for handling muck at the bottom are (a) use a chute gate at the next lower level and load directly into a muck train, and (b) use a mucking machine to load the train.

244. Raises can be concrete lined after they are completed as in raise boring, or lined as they are raised. Because the mucking activity does not interfere with the drilling, blasting, and timbering activity, raises can progress at about twice the rate of conventional shaft sinking. Conventional raising, however, takes longer and costs more than raise boring (Cummins, 1973).

Raise Boring

245. Raise boring is the process of drilling large-diameter holes, usually between a mine level and the surface or between mine levels. This method requires both ends of the raise to be accessible, the upper to locate the machine, and the lower to drill a pilot hole into and attach the cutterhead.

The raise boring machine mounted at the upper end supplies the torque and thrust necessary to rotate the cutterhead and fragment the rock (Cummins, 1973). Figure 48 illustrates the principle of raise boring. Figure 49 shows a raise drill, and Figure 50 shows the cutterhead and bits.

246. The first raise boring machines were developed in Germany and Japan in about 1950. In the United States, the first raise bored with equipment designed for this purpose was at the Homer Wauseca Mine in Michigan in 1962. It utilized a 7-in. pilot hole that was reamed to 3 ft diam. Raise boring had a slow start with only 12 machines in use by 1967. By 1970, the number had increased to 80. Today, well over 300 are in use worldwide (Monroe, 1980).

247. The major components are drill rods, stabilizers, cutters, and cutterheads. The drill rods are usually about 5 ft long and the stabilizers control pilot hole deviation. The cutters are the rock-breaking portion of the cutterhead. A pilot hole bit would typically contain three cutters. The raise bore cutterhead uses from 6 to more than 25 cutters. Raise boring equipment has a high reliability similar to large-diameter drilling, and is relatively easy to maintain because the raise boring machine is on the surface.

248. The largest raise drill available today, the RBM-211, was built for Frontier Kemper by Ingersoll Rand. It has a head that can, by bolting on different size bit configurations, bore from 12- to 20-ft-diam holes. The largest diameter bored by this machine was 20 ft, 3 in. for Monterey Coal in Illinois in 1978. Recently a 20-in.-diam drill string was manufactured for the Hughes CSD 820. This drill string is designed for boring 20-ft-diam shafts or larger and is currently being used by Santa Fe International for drilling a 14-ft shaft in Australia. The CSD 820 is a combination large-diameter drill/raise borer which can, like the RBM-211, bore large-diameter shafts.

249. Hydraulic, fixed-speed electric, and variable-speed electric are the three main power types. Hydraulic machines are durable, reliable, and can stand substantial shock. A fixed-speed electric drive can transmit a sudden surge of power through the system which may damage the system components. Maintenance of variable speed electric drives is often beyond the capability of maintenance personnel (Monroe, 1980). Current models of raise borers produce 45,000 to 450,000 ft-lb of torque. The larger machines are capable of over 1,000,000 lb of thrust.

250. Most raise boring machines can be easily disassembled, transported, and assembled, which facilitates their use throughout the mine. Often a two-man crew is adequate for machine operation, usually an operator and a helper. Additional labor should be available to speed up moving the equipment and connecting the reamer head.

251. Prior to the start of boring, a site must be excavated to accommodate the machine. The height of the drill station must be sufficient to permit an adequate concrete pad thickness. Service facilities must also be installed. After the drill site is prepared, the drill is moved to the site, and the machine is aligned with the help of a survey crew. An up-boring rig is held in place by the bolts in the concrete pad. Drilling begins with the pilot bit followed by a stabilizer, and then drill rods alternating with stabilizers. The number of stabilizers required depends on the rock conditions encountered. The rods are added at the drill until the hole is completed. The pilot bit and nearby stabilizer are removed and the reaming head is then installed. As the reaming proceeds, the rods are removed until the reaming head has opened the shaft to the machine.

252. Removal of cuttings in the down-drilled pilot hole is done conventionally with air or water. The raise borer cuttings fall by gravity to the bottom of the hole where they can be picked up by a mucking machine. When the machine is positioned below the raise, as in raise boring, cuttings from both operations are deflected to a chute where they can be loaded and hauled away.

253. The main advantage of raise boring is the high shaft boring speed relative to conventional shaft sinking (Cobbs and Reeder, 1974). Other advantages are: (a) improved safety, (b) relatively low cost, (c) round opening with no blasting fractures, and (d) reduced labor (Engineering and Mining Journal, 1981).

254. The major disadvantage of raise boring is that it requires access to both ends of the raise. Also, because miners do not have access to the raise until the boring is complete, large flows of groundwater cause serious problems. Pregrouting or some other form of stabilization prior to boring the shaft usually reduces this problem.

255. For large-diameter raises (15-20 ft), an average advance rate is 2 ft/hr. A faster advance rate of 5 ft/hr can be expected for smaller (8-12 ft) diameter raises. For pilot holes, an average near 5 ft/hr may be expected.

256. The leading supplier of raise boring machines is the Robbins Company, Kent, Wash. They design as well as manufacture their machines, but recently purchased the very successful Ingersoll Rand line. Other suppliers include Dresser Industries, Tamrock, and Subterranean Tools.

257. Estimating costs of raise bored shafts is difficult and it depends heavily on the method the contractor uses to amortize the equipment costs, because raise boring is equipment-intensive. Capital costs can be amortized over any number of years or number of shafts depending on the contractor's accounting system and his financial and competitive position. Most contractors try to recover as much of the new equipment costs as possible on the first project.

258. Generally, 16- to 20-ft-diam raise boring costs are about half that of conventional shafts and about two-thirds of large-diameter drilled shafts.

259. A rough approximation of raise boring costs can be made through a hypothetical case assuming the following: 16-ft-diam shaft at 1,000 ft depth, a 1 ft/hr average rate at 75 percent utilization of the machine, capital costs amortized over three years and two shaft projects per year, \$200/ft cutter replacement costs, and a 20 percent profit on equipment and labor.

260. The following is based on estimates obtained from industry sources (Telecon, Tom Lundstedt, The Robbins Co., 3 August 1982):

Capital cost:

$$\frac{\$2.8\text{ M(Machine)} + \$2\text{M (Drill Rod)} + \$6\text{M (Accessories)}}{\text{(3 year amortization)(2 shafts/year)}} = \$\ 900{,}000/\text{shaft}$$

Operating cost:

$$\frac{\text{(1,000 ft depth)(\$3,500 labor/day)}}{\text{(24 hrs)(75 percent machine utilization)(1 ft/hr advance)}} = \$\ 200{,}000$$

Cutter cost:
(\$200/ft)(1,000 ft) = \$ 200,000

Collar and bottom station	\$ 300,000
	\$1,600,000
Profit (20 percent)	320,000
	\$1,920,000

261. Therefore, this hypothetical case costs about $2,000/ft without a lining. The $2,000/ft plus the lining cost, amounts to roughly half of the conventional sinking cost of $4,000 to $6,000/ft. Costs are less for smaller-diameter shafts, at about $300/ft on a 6-ft-diam shaft.

Blind Hole Raise Boring

262. Boring blind holes from the bottom up ("boxhole" boring) is the most recent technique in mechanical raise boring. This method does not require a pilot hole because the machine drives the head from below.

263. The boring machine is assembled in the drift below the raise location. The head is collared into the rock, and the raise continues by pushing the head up, adding drill rods and an occasional stabilizer until the raise is completed.

264. Most machines are self-contained units including power pack, controls, hydraulic thrust cylinders, guide posts to align the drill string, hydraulic or electric motors for torque, a device to hold the drill string while pipe and stabilizers are added, and a means of deflecting, collecting, and loading cuttings.

265. The machine supplies the thrust and torque required through the drill string. The drill string consists of drill rods, stabilizers, and cutting head.

266. The Calweld Company developed the Vertical Thrust Borer (VTB) in 1967 for use in New Mexico uranium mines, and the Model BH 80 for the South African gold mines. The Calweld VTB is still being used with few changes in the soft sandstone for which it was designed (Smith, 1980).

267. Both the Calweld and another blind hole raise machine, built by Subterranean, transmit torque and thrust along the drill string which is threaded rotating drill pipe.

268. In 1975, some machine modifications were made. The Subterranean UR-60 utilized a projecting pilot bit on the cutterhead which improved directional accuracy. The Robbins 52-R machine transmits only thrust through the drill string. Torque is obtained through a hydraulic motor attached to a gear case just below the cutting head. Hydraulic fluid is pumped through hoses within the drill string. Robbins' more recent 55-R uses an electric drive instead of the hydraulic drive.

269. In boxhole boring, stabilizing and centering the drill string is essential. Nonrotating stabilizers are used near the head, or a stringer mounted on the cutterhead reduces the tendency of the bore to drift.

270. Diameters range from 4 to 7 ft. Raise lengths start at 50 ft and extend to 300 ft. Most holes are drilled in the 100- to 200-ft range.

271. In sandstones, an advance rate of about 5 ft/hr can be achieved in rock with less than 5,000-psi unconfined compressive strength. In rock of 35,000 psi unconfined compressive strength, a rate of 3 to 4 ft/hr is possible; however, the rate drops to 1 ft/hr in rock of 50,000 psi.

272. Most of the current machines are self-erecting and the reliability is consistent with other mining equipment.

273. Boxhole boring is not competitive with conventional raise boring as costs rapidly increased with hole lengths over 200 ft. Hole diameters have not exceeded 7 ft.

274. While the boxhole borer is not applicable for all situations, it has achieved a position as a routine production unit in many mines.

Large-Diameter Drilling

275. Large-diameter drilling (LDD) or big-hole drilling (BHD) is a mechanized shaft sinking method that has evolved from the oil well drilling industry. The vast experience gained through oil well drilling has provided safe procedures and reliable equipment that only had to be increased in size and slightly modified to meet big-hole needs. A major modification was the introduction of a reverse circulation method to aid cleaning the cuttings from the much larger face (Lackey, 1983).

276. LDD is usually considered to be applicable for hole sizes over about 2 ft in diameter. Most have been 8 to 9 ft with a few at or near 12 ft. A 16-ft, 6-in.-diam hole was sunk by Kerr McGee at Grants, N. Mex., in 1968, and the Dutch sank a 25-ft-diam shaft in 1958, but both were multipass or reamed shafts (Telecon, Gene Skinner, Bureau of Mines, July 1982). Most LDD shafts drilled at the Nevada Test Site were for underground nuclear testing; over 450 such shafts ranging from 4 to 10 ft in diameter and from about 500 to over 1600 ft deep have been drilled at NTS since 1961. Through this large government program, LDD technology advanced swiftly and broadly. Trained crews and numerous drilling rigs are now available, and equipment and procedures are such that the systems can be rapidly mobilized and demobilized.

277. Most drilling, however, has been in the relatively competent rock of the Nevada Test Site, where strong financial resources were available. Strong financial backing is necessary because a serious shortcoming of LDD is the possibility of losing the cutterhead from a drill string failure or an unwound joint. "Fishing" for a tool is costly and has forced drilling contractors to seek contracts paying costs per day rather than the fixed price contracts preferred by the mining community. This type of contracting, where the sponsor needs to share the risk of poor performance, has kept LDD out of the mining sector with its large commercial market for shafts. Therefore, unlike conventional sinking, experience with larger-diameter shafts sunk under a wide range of drilling conditions is somewhat limited.

278. In the mid-seventies, the Bureau of Mines awarded a study and test contract for developing a much larger rig than existed for drilling and lining a 20-ft-diam shaft to 2,000 ft. Subsequently, the Hughes Tool Company built a system capable of 20 ft in diameter for Santa Fe International. About two dozen drill rigs are considered big-hole rigs, capable of drilling 10- to 12-ft-diam holes. Contractors owning such rigs include Camay Drilling, Loffland Brothers, Challenger, Santa Fe International, Rowan Drilling, and Zeni Brothers. More rigs are available because recent interest in drilling for deeper oil has required drill rigs with hook loads similar to those of LDD.

279. LDD requires the following: a drill mast and draw works to lift the drill assembly in and out of the hole, a cutterhead to cut the face and move the cuttings to the pickup point, donut weights and stabilizers above the cutterhead to stabilize the cutterhead and provide a straight hole, and a drill pipe to act as a conduit for removal of cuttings. Torque may be transmitted from the turntable on the platform to the cutterhead through the drill string or applied by hydraulic motors mounted near the cutterhead. In the latter case the drill pipe does not rotate but transmits normal forces to the cutterhead.

280. Air compressors and water pumps for lifting the cuttings to the surface through the drill pipe, and a tailings pond for reclaiming the water or mud are also required. Drill rigs are usually rated by hook load, which is the weight of drill string it can lift. Big hole tools are much heavier than oil drilling tools and require 1 to 2 million lb hook loads. Figure 51 shows a typical drill string assembly.

281. Circulation fluids can range from plain water to elaborate combinations of drilling muds and chemical additives to control water loss through the formation, hold back water inflows, support the shaft walls, and protect the freshly cut rock from deterioration. Some mud properties to be considered are weight, viscosity, pH, and chloride ion. Because the weight of the mud column neutralizes water inflow, drilling is preferred where a large water inflow is expected. Figure 52 shows the flow within a reverse circulation system. The large drill rig and mud ponds require about 5 acres. When the cutters become worn and must be replaced, a bit run or trip is made. The hook lifts the string, and the pipe sections are removed one at a time until the cutterhead is above the shaft. The string reenters the shaft in a reverse sequence.

282. All drilled holes to date utilize liners of steel casing designed for full hydrostatic head. This may require thicknesses of 2 in. and stiffener rings spaced less than 24 in. apart. The liners are prefabricated in up to 80-ft lengths, and are welded together and x-rayed on the rig floor as they are lowered into the hole. Most of the hook load capacity is used in lowering the liner, even when the liner must be floated down (temporarily sealing the liner bottom and floating it in the mud or water as the mud or water is pumped down). Once in place, the liner is cemented to the wall through pipes tacked to the outside of the casing as in backwall grouting. Alternates to steel casings for drilled shafts have been investigated by both the government and industry, because steel is generally too expensive for commercial shafts. Promising designs for concrete liners have been prepared, but none have been field-tested. Steel casing has the advantage of assuring a dry shaft without water rings, pumpout holes, and not requiring men in the shaft for installation. There are limits to the weight and, therefore, liner diameters the rigs can handle.

283. Penetration rates generally average 1 ft/hr, but over 10 ft/hr is possible in very soft formations (Telecon, Duane Lackey, Reynolds Electrical and Engineering Co., 23 July 1982). Lackey (1983) reported sustained penetration rates of 12 ft/hr on a 96-in. shaft at the Nevada Test Site. Even though penetration rates are low, good daily progress can be made with small crews drilling three shifts a day and often drilling can proceed for days without pulling the drill string to change cutters.

284. A commercially financed shaft drilling project was recently completed at Crown Point (Hunter, 1981). Two 6-ft-diam shafts and one 10-ft-diam shaft were drilled to about 2,200 ft and lined with steel. The project was completed under budget and ahead of schedule in 363 days, including mobilization and demobilization. The shafts were about 100 ft apart and the drill rig could be slid to the other sites after being assembled over the first shaft. A large amount of groundwater was a factor in choosing drilling for this project.

285. The equipment specifications for the LDD used on the Crown Point project are as follows:

Mast	
Gross nominal capacity	1,300,000 lb
Static hook load capacity	1,000,000 lb
Height	112 ft
Substructure	
Set back load	1,000,000 lb
Racking capacity - 13 3/8 in.	3,600 ft
Height	6 1/2 ft
Rotary beam cap	1,000,000 lb
Rotary table - 37 1/2 in.	650 tons
Crown block	750 tons
Traveling block	750 tons
Hook	500 tons
Swivel - 12 in. I.D.	750 tons
Kelly - 14 in. x 42 in.	500 tons
Drill Pipe - 13 3/8 in. x 30 ft	
H-490	
Tensile yield strength - minimum	1,087,000 lb
Torsional yield strength - minimum	200,000 ft-lb
Weight	90 lb/ft
Drill collar mandrel	
Flange size	60 in.
Length	47 1/2 ft
Drawworks - national .125	1,250 hp
Drawworks power-hoisting 2 Cat D-379 engines	1,230 hp

Hoisting load, speed, and horsepower	
Buoyed string weight at 2243 ft	550,000 lb
Hoisting speed off Bottom-max	42 fpm
Hook horsepower requirement	700 hp
Rotary speeds	0-30 rpm
Tugger hoists (5)	
1 - top dwwks	15,000 lb
2 - floor	10,000 lb
1 - cat walk	5,000 lb
1 - gyro survey hoist	2,000 lb

286. The statistics for the performance of the LDD used at Crown Point (Hunter, 1981) are as follows:

For the 10-ft-diam shaft (Shaft No. 1):

a. Twelve bit runs were made in 2,243 ft.

b. The bit rotated 96 days out of 129 drilling days (74 percent utilization).

c. Average speed was 11 rpm.

d. Average instantaneous penetration rate was 0.98 ft/hr or 17.39 ft/day overall.

e. Average weight on the bit was 100,000 lb.

f. Total time to complete, including the 12 days for the initial mobilization, was 183 days.

For the first 6-ft-diam shaft (Shaft No. 2):

a. Nine bit runs were made in 2,188 ft.

b. The bit rotated 51 days out of 62 drilling days (80 percent utilization).

c. Average speed was 18 rpm.

d. Average instantaneous penetration was 1.80 ft/hr or 36.46 ft/day overall.

e. Average weight on the bit was 70,000 lb.

f. Total time to complete, including sliding rig from Shaft No. 1 to Shaft No. 2, setting steel liner, backwall grouting, and pumping shaft dry was 90 days.

287. The statistics on the second 6-ft-diam shaft were nearly the same as for the first 6-ft-diam shaft.

288. Two fishing jobs were required, one to recover an air line and another to recover a cutter lost off the cutterhead.

Cost

289. Comparative costs for Shaft No. 1 were reported by Hunter (1983). Site preparation accounted for 6.9 percent of the total costs, capital costs of the rig were 20.2 percent, mud and air were 8.9 percent, bits and stabilizers were 10.9 percent, casing, casing welding, and cementing were 39.9 percent, and other expenses including fuel, supervision, quality control, taxes, logging, surveying, and cuttings disposal accounted for the remaining 13.2 percent of the total costs. If the daily costs are assumed to be $50,000, the total cost for Shaft No. 1, completed in 183 days, would be $9,150,000, or $4,079/ft for the 2243-ft-deep shaft. Hunter reported the 10-ft shaft represented 53 percent of the total project cost. The 6-ft-diam shafts accounted for 24 and 23 percent, respectively, for Shafts No. 2 and 3. If the $9,150,000 is a reasonable estimate for the 10-ft shaft, then the 6-ft-diam shafts cost about $4,140,000 each, or slightly less than half as much as the 10-ft-diam shaft.

290. A detailed cost comparison between conventional shaft sinking and shaft drilling of a 20-ft-diam and 1,000-ft-deep shaft was done under contract to the government (Schalge and Smith, 1981). The costs were estimated to be nearly the same at $3 million (1978) for a concrete-lined shaft, including an 18 percent profit. The drilled shaft estimates were based on a $9 million investment in drilling equipment amortized over 24 shafts at four shafts per year.

291. The 1978 conventional costs (without profit) were found to vary from $2.3 million to $4 million depending on differences in shaft location and sinking problems. Drilling costs were most sensitive to the time required to complete the shaft. The break-even cost with conventional shaft sinking occurs at about 4.5 months or 135 days (note that the Crown Point shaft of one-half the diameter required 183 days to complete). Costs were estimated to increase at about $4,000/month for drilling time beyond 4.5 months.

292. Industry records (1982) show an average $45,000 to $50,000 per day overall cost (drilling and lining) if the total days (including mobilization and demobilization) are used (Telecon, Hassel Hunter, Conoco, Inc., 23 July 1982). The lining costs include the steel cost ($0.75 per delivered pound), fabrication, lowering, and cementing and may amount to two-thirds of the project cost (Lackey, 1983). Larger shaft diameters increase cost through reduced drilling rates, therefore increasing the days on site. Core samples

can be sent to drilling equipment designers and manufacturers for drillability analysis. Their estimates of drilling rate, in conjunction with other costs that are known, are used to estimate total cost. The accuracy of estimates varies but can be as close as 1 percent.

Reaming

293. Reaming is the mechanical enlargement of a shaft, by either drilling and blasting or boring such as raise drilling. If the shaft is enlarged through drill and blast means, the process is usually referred to as slashing. Reaming allows the construction of larger-diameter shafts at a lower design horsepower. Slashing is advantageous in that conventional techniques are greatly simplified when rock can be broken to an open area and the muck can be disposed of by gravity.

294. Except for the 20-ft-diam shaft raise drilled by Frontier Kemper in southern Illinois, shafts over 12 to 14 ft have all been multipass, e.g., the previously mentioned 16-ft, 6-in.-diam drilled shaft at Ambrosia Lake by Kerr-McGee, and the 25-ft-diam shaft sunk by the Dutch in 1958.

295. No particular difficulties are encountered with reaming or slashing, provided that the torque and thrust limitations of the equipment are not exceeded. Even though raise boring actually enlarges the drill-rod pilot hole, it is not formally considered a reaming process. The Wirth V-Mole machine operated by Thyssen is considered a reamer. A diagram of the machine is shown in Figure 53. These machines have been used in German coal mines since the early 1970's.

296. The Wirth machine is in its third generation, and construction of a fourth has begun. Its maintenance, reliability, rate of penetration, and cost are impressive, and have all been demonstrated through the successful application to many shafts. The most recent project, and the first in this country, is the Thyssen project at Bessemer, Ala., where three shafts have been sunk at the same site at the Jim Walters Resource mines in 1981-82 using the third-generation machine SB VII 650/850 (Hanke and Gabitzsch, 1983). A 5-ft-diam shaft for mucking was first raise-drilled (8-ft-diam for the last two shafts); then the 23-ft-diam shaft was reamed from the top down with a machine similar to a vertical TBM but without a muck pickup system. These shafts were 1670 to 2040 ft deep. Because the operator need only do a

preoperational check each day, and the routine maintenance is performed only once a week, high utilization of the machine is possible. The cuttings are cleared by using a cutterhead inclined so that the cuttings move by gravity to the raise-bored central shaft without any assistance.

297. Machines like the Thyssen could be designed to ream very large-diameter shafts. Theoretically, the cost per unit volume of shaft should decrease as the shaft volume increases because the capital equipment can be amortized over a larger volume.

298. Reaming, like raise boring, must have a pilot hole and must have an existing opening below the shaft for collecting muck. The Wirth concept was inspired by the extensive underground workings that already exist in the European coal mining districts. In the United States, where many shafts are needed for opening new mines, the need for blind shaft boring equipment is greater (see blind shaft boring section for description of Wirth attempt to use the V-Mole for blind shaft applications).

299. The V-Mole is similar in some respects to the Robbins' Blind Shaft Borer (BSB) design, discussed later, except no muck handling system is needed. The Wirth machine bores shafts from about 17 ft to 23 ft in diameter, weighs 240 tons, stands 45 ft high, and has 1,100 design hp. It has only one laser for guidance and needs no ventilation system if adequate ventilation air is moving through the 5-ft pilot hole. The machine uses the pilot hole only for muck removal and bores a shaft guided only by the laser. If the machine bores off the pilot hole, it is essentially boring blind at the face of the cutterhead.

300. The machine is now in Bessemer, Ala., boring through rock consisting of thin formations with over 40,000-psi compressive strength and some thick formations at 7,300 to 17,500 psi. Average advance rates for three shifts/day and 5 days/week were 23 ft/day without lining for the first shaft, 29 ft/day for the second shaft, and 59 ft/day for the third shaft. Shaft lining advanced at an average rate of 21 to 31 ft/day. The actual time the machine operated, based on a 24-hr day, has been between 28 and 46 percent. Mobilization and demobilization have taken 17 to 18 weeks each. Actual drilling time was 13 weeks for the first shaft, 11 weeks for the second, and 6 weeks for the third.

301. Construction of a fourth shaft is under way and is expected to be completed more quickly than the preceding shafts. Support for this shaft will

be rock bolts and wire mesh; the concrete lining was eliminated after the second shaft as being unnecessary. The V-Mole method of shaft drilling has proven advantages in speed and safety if the right ground conditions and access to both ends of the shaft exists. The ground must be self-supporting with minimal groundwater inflows and strong enough to withstand the gripper pad bearing pressures. Under suitable conditions, the V-Mole is up to twice as fast as conventional construction and less expensive because of the time saved, the reduced support requirements, and inherent safety.

Blind Shaft Boring

302. Blind shaft boring is the mechanical sinking of a shaft from the surface without a pilot hole or tunnel to dispose of the muck. The term "blind shaft borer" differs from large-diameter drilling (LDD) in that miners operate the borer downhole as they do tunnel borers.

Robbins Blind Shaft Borer

303. In the mid-seventies there was a growing awareness of the possible need to dramatically increase coal production. The number of blind shafts needed was estimated in the hundreds. To accomplish this, the Bureau of Mines and later the Department of Energy (DOE) funded the development of a blind shaft borer (Amstutz and Danowski, 1982).

304. Only about three BSB machines have been built, the most recent being the Bureau of Mines/The Robbins Co. machine. This machine was only partly successful, but the lessons learned plus the results of other research work done by the Bureau and Department of Energy provide a strong basis for building a machine that meets the original goals (Amstutz and Danowski, 1982). This machine is now in storage at the Nevada Test Site and could be rebuilt. The concept is applicable to diameters over about 14 ft, but the existing machine has a set diameter of 24 ft. Size is not much of a hindrance to boring rate, in the same manner that size does not necessarily hinder the rates of tunnel borers. In fact, the BSB is closely related to the tunnel borer in most respects except it bores vertically instead of horizontally.

305. The machine is 60 ft high, 24 ft in diam, and weighs over 300 tons. It has 1,000 design hp and requires about eight men to both operate the machine and line the shaft behind the machine. It provides ventilation, lighting, communications, and meets most of the many health and safety requirements of the State and Federal regulatory agencies.

306. The machine was designed to bore and line at a rate of 20 ft/day, or about four times that of conventional shaft sinking. It was designed to reach instantaneous advance rates of 5 ft/hr and average 3 ft/hr. At this average rate, the machine utilization required (after maintenance, regripping, shift changes, and service extensions) would only need to be 30 percent to meet 20 ft/day. Tunnel borers, for example, can attain 50 percent utilization. The machine operates similarly to a tunnel borer in that it grips the walls, thrusts the head against the rock face, advances the gripper after about 30 in. of boring, regrips, and then repeats the cycle. After about 20 ft of advance, the services and the lining are extended in preparation for another 20 ft advance. The machine is shown in Figure 54. Specifications are given in Appendix A.

307. Problems during start-up were not completely eliminated, but some of the minor troubles, such as misconnected hoses, were resolved. Problems with the mechanical muck system continued throughout the project. The retrofit flight conveyors were of marginal benefit over the on-site modifications to the originals. The bucket elevator power problems increased significantly as the fixed center scrapers wore and allowed muck to build up on the face.

308. The skip hoisting system required modifications to minimize leakage of wet muck and continually exhibited sequencing problems. The hydraulic problems were intensified for a period because of addition of an incompatible fluid to the system. The hydraulic problems became worse as pressures were raised in efforts to improve performance. The lubrication system suffered from contamination with subsequent wear problems.

309. The permissible (acceptable to MSHA) electrical devices corroded as a result of the wet, dirty environment in which the BSB operated. The time required for lining with concrete and advancing the services was approximately three times greater than the scheduled 8 hours. The boring and lining problems necessitated operation in a cyclic, rather than continuous, fashion.

310. The hydraulic system was significantly different from the system on a tunnel borer and excessively complex. In addition to the usual tunnel borers' cylinders (propel, gripper, torque, and steering-side support cylinders), there were two flight conveyor motors, two bucket elevator motors, and a hydraulic-driven lubrication system, all of which greatly increased the volume of hydraulic fluid in use. The high-flow volume problems were compounded by the use of fire-resistant fluid.

311. The laser guidance system had convergence and divergence problems below the 450 ft depth, resulting in the loss of considerable boring time. The muck disposal ponds were not initially designed with expectations of boring wet, so treatment and disposal of shaft water became a problem.

312. All of the problems encountered could be rectified on a future machine, based on existing technology and recent testing. The Radmark Company, under contract to the Bureau of Mines, tested a full-scale pneumatic hoisting system for the BSB at an abandoned eastern mine (Radmark Engineering, 1978) (see Figure 55). It successfully hoisted 200 tons/hour to 1,200 ft. This system would increase the reliability of the mucking system by removing much equipment, reducing the height of the machine, improving the operation by separating the boring activity from the lining activity (all boring done on the borer, and all lining confined to the Galloway stage), and increasing the mucking rate even in wet conditions. This system is now in storage at the Nevada Test Site, and is available for use with little modification. It includes compressors, pipe-handling system, and auxiliary equipment, all permanently mounted on trailers, so that it can be moved quickly onto the site and connected to the machine in less than a week. Air and material pipes can be lowered as the machine progresses down to depths over 1,800 ft. The installed horsepower is 1,700 and could be increased to maintain a 200 tons/hr rate to over 3,000-ft depths. Also, a vacuum system was built to pick up the cuttings from the face and convey them 30 ft vertically to the pneumatic hoist. This vacuum system was tested on a full-scale fixture where it also conveyed 200 tons/hr. A much smaller vacuum system was used on the Dravo machine with some success in the late sixties. Vacuum and pneumatic systems can transport muck varying over a wide range of moisture contents. For dry muck, water may be added at the face or at the pickup head to increase the moisture content of the cuttings to between 4 and 10 percent. Increasing the moisture content of dry muck increases the hydraulic efficiency of the system. Most equipment in the vacuum and pneumatic systems is off-the-shelf and used extensively in other applications. A working vacuum/pneumatic system would eliminate the mechanical pickup, bucket elevator, and skip hoist, which is a high-maintenance and low-capacity system.

313. New and simpler designs are needed for the hydraulic and lubrication systems to increase their reliability. Highly reliable systems are common on other equipment, and could be incorporated on this machine.

The steeply inclined cutterhead, used previously by Dravo and currently by the Wirth machine, has been very successful and should replace the existing head. The ventilation and water-handling systems require relatively simple changes.

314. The lining system used on the Wirth machine and also by Thyssen in Alabama could be used. This step-form lining system has attained a rate approaching 100 ft/day and could be easily adapted to the BSB. Weaknesses in the laser guidance system, because of convergence of the laser beam, could be eliminated simply by moving the laser guns down the shaft in 400-ft increments.

315. Each modification proposed here either has been tested or has been used successfully in some other application. With these modifications, the machine should meet the goals and should average 3 ft/hr while the machine is available for boring.

316. The system specifications and the companies involved in the project are listed in Appendix A.

317. A hypothetical cost comparison between the blind shaft borer and conventional sinking was conducted by the Paul Weir Company in 1978 to define the economic advantages or disadvantages of one method over another. The cost evaluation compares the time and cost of one mine shaft constructed by the BSB (assuming a sinking rate of 20 ft/day) with that of one constructed using conventional methods. Also, the potential of this machine to improve the time required to open up a new mine was estimated. All costs are expressed in April 1978 dollars.

318. In making the estimates, the following assumptions and qualifications were used. The total depth was approximately 1,500 ft. The shaft would be concrete-lined throughout to a finished inside diameter of 22 ft (minimum concrete thickness = 12 in.). The shaft collar would not require grouting, freezing, piling or caisson work before excavation and concreting, and collar depth was assumed to be 50 ft. The shaft would be sunk through strata requiring no temporary support and inflows would be less than 25 gpm, and the gravel would be pregrouted from the surface through at least four holes spaced uniformly around the shaft periphery. The shaft would include a station at the bottom that extends 30 ft horizontally in two directions from the shaft. The site was assumed level with good access roads and sufficient electrical power and water.

319. To estimate time-sensitive costs for both methods of shaft construction, bar charts or schedules of construction were prepared showing the

time required and sequence of events from the time of agreement to proceed with construction equipment from the mine site.

320. The comparison of the two methods indicated the following:

- a. The shaft could be completed in 37 weeks using the blind shaft boring machine at an anticipated 125 ft of completed shaft per week.
- b. The time required to complete an identical shaft using the conventional (drill and blast) method would be 75 weeks, twice as long as the BSB. The crews' performance was assumed to improve over the first 200 ft of shaft, and eventually attain an average of 30 ft of completed shaft per week.
- c. The cost of shaft construction, using the boring machine, was estimated to be \$3.89 million (assuming April 1978 costs and full depreciation of the machine after 5 years or 10 shafts). The comparable conventional shaft cost was estimated at \$4.63 million.

Wirth blind shaft borer

321. A machine called a V-Mole, discussed earlier, was built by Wirth, Inc., of Germany to bore vertically using a pilot hole for passing cuttings to an entry below. This machine has been so successful in this mode that a hydraulic pickup and hoisting system was installed, and the system was used in a blind shaft. The machine was pulled from the shaft, the hydraulic pickup system was modified, and the hydraulic hoist supposedly replaced with either a skip or pneumatic hoist. The DOE/Bureau of Mines, in cooperation with Thyssen Mining Construction Inc., initiated plans to test a Wirth machine with a pneumatic hoisting/vacuum pickup system based on DOE test results. No knowledge is presently available on the hydraulic modifications, and the vacuum/pneumatic option has not been pursued by DOE nor the Bureau of Mines.

Summary and Comparison of Shaft Construction Methods

322. Most United States shafts have been sunk by the conventional method, i.e., drilling, blasting, loading, and hoisting the broken rock to the surface. Drilling is done by handheld sinker drills or multiple drill jumbos. Several muck loading systems have been developed that are particularly adapted to shaft sinking, but muck hoisting is usually done with bucket-cable-hoist combination. Sinking rates vary from about 70 to 300 ft/month, although over 1,200 ft/month has been attained in South Africa. Low rates are usually a result of excessive overburden, excessive groundwater, incompetent ground,

equipment breakdown, labor problems, poor supervision, or an inexperienced crew. However, conventional shaft sinking is relatively flexible, can cope with high water inflows and poor ground, and is a highly reliable method under most conditions. Compared with other shaft sinking methods, capital costs are low and labor costs are high since operation requires different skills but relatively simple equipment. Skilled shaft sinkers are becoming increasingly scarce. Costs vary widely depending on conditions, i.e., size, depth, location, and ground conditions. An impactor, developed by the Bureau of Mines, substitutes for drilling and blasting and has shown its potential ability to cut costs and speed up development. The techniques for inclined shafts are similar to those of vertical shaft sinking. No new techniques or equipment are available that could markedly increase conventional shaft sinking rates.

323. Conventional drill and blast shaft raising is used mainly for short shafts connecting mine levels. Muck removal is by gravity; support usually consists of timber sets. Concrete lining may be installed later. Ventilation is difficult and the work is generally more hazardous than conventional shaft sinking, but is usually faster because of the time saved in mucking.

324. Raise boring is a system for boring to the surface from a mine level or between mine levels. A pilot hole is first drilled and then enlarged by a machine mounted on the surface which pulls and turns a cutterhead mounted at the end of the drill rod. A disadvantage is that both the top and bottom of the shaft must be accessible and the depth of the shaft it can bore is limited. However, it is a relatively safe, low cost method. Several blind raise borers (boxhole drills) have been built. These machines push the cutterhead from below, without a pilot hole, but the shaft height is limited to about 300 ft. Raise boring costs are about half of conventional sinking and about two-thirds of large-diameter drilling. The largest existing raise borers can bore shafts 18 to 20 ft in diameter to 1,000 ft deep, or smaller diameters to greater depths.

325. Large-diameter drilling uses oil well drilling technology. Shafts over 10 ft in diameter have been drilled, but the method is best for smaller diameters. Only vertical shafts can be drilled in the larger diameters. No underground miners are required because drilling and muck removal are handled on the surface. About two dozen United States drill rigs currently have the capacity to drill large-diameter shafts, and many well trained crews

are available. The principle disadvantage is the slow penetration rate for large-diameter shafts in hard ground, partly because of the poor muck removal rates. The cost of rigs capable of drilling 10-ft-diam shafts is about $50,000/day overall, but rigs for larger-diameter holes can cost more. The equipment is easily maintained, very reliable, and able to drill continuously. The linings have always been welded steel casings designed for full hydrostatic pressures, which are very expensive, accounting for up to two-thirds of the shaft cost.

326. Reaming is the sequential enlargement of a shaft, beginning with a central pilot hole. Most larger shafts (12 to 14 ft in diameter) have been reamed in multiple passes. Reaming, like raise boring, requires both ends of the shaft to be accessible. The Wirth V-Mole is a special type of rodless downhole reamer, similar in some respects to the blind shaft borer, but without a muck pickup and removal system. Muck removal is instead accomplished by gravity through the central pilot hole.

327. A blind shaft borer is essentially a TBM that has been modified to bore vertically. A rotating cutterhead with roller cutters breaks the rock. For the borer to reach its potential for rapid development, a special system must pick up the muck from the face and transport it to the surface, but these systems have generally been inadequate. A European test on a hydraulic system, and a mechanical system used on a government sponsored blind shaft borer development project have both performed poorly. A combination vacuum-pickup, air-transport system was tested and appears the best, but it has not yet been used in the field. System reliability and maintainability are poor but can be improved to match that of a tunnel borer. The main advantage of the blind shaft borer would be a sinking rate up to four times faster than with conventional shaft sinking at a comparable cost. Also support and lining requirements may be lower in dry shafts because there is less damage to the rock from boring than from blasting.

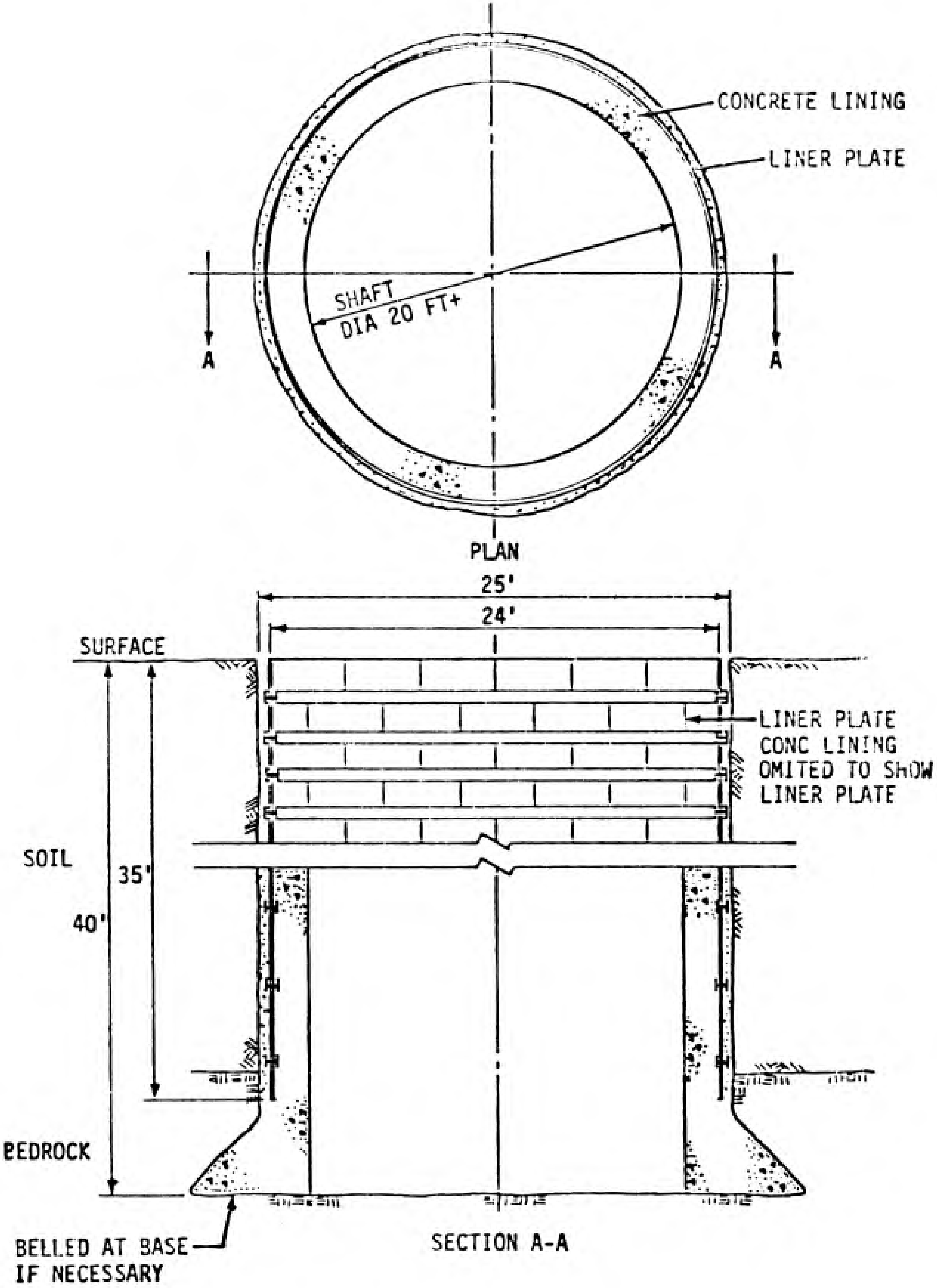


Figure 37. Cast-in-place shaft collar inside liner plate

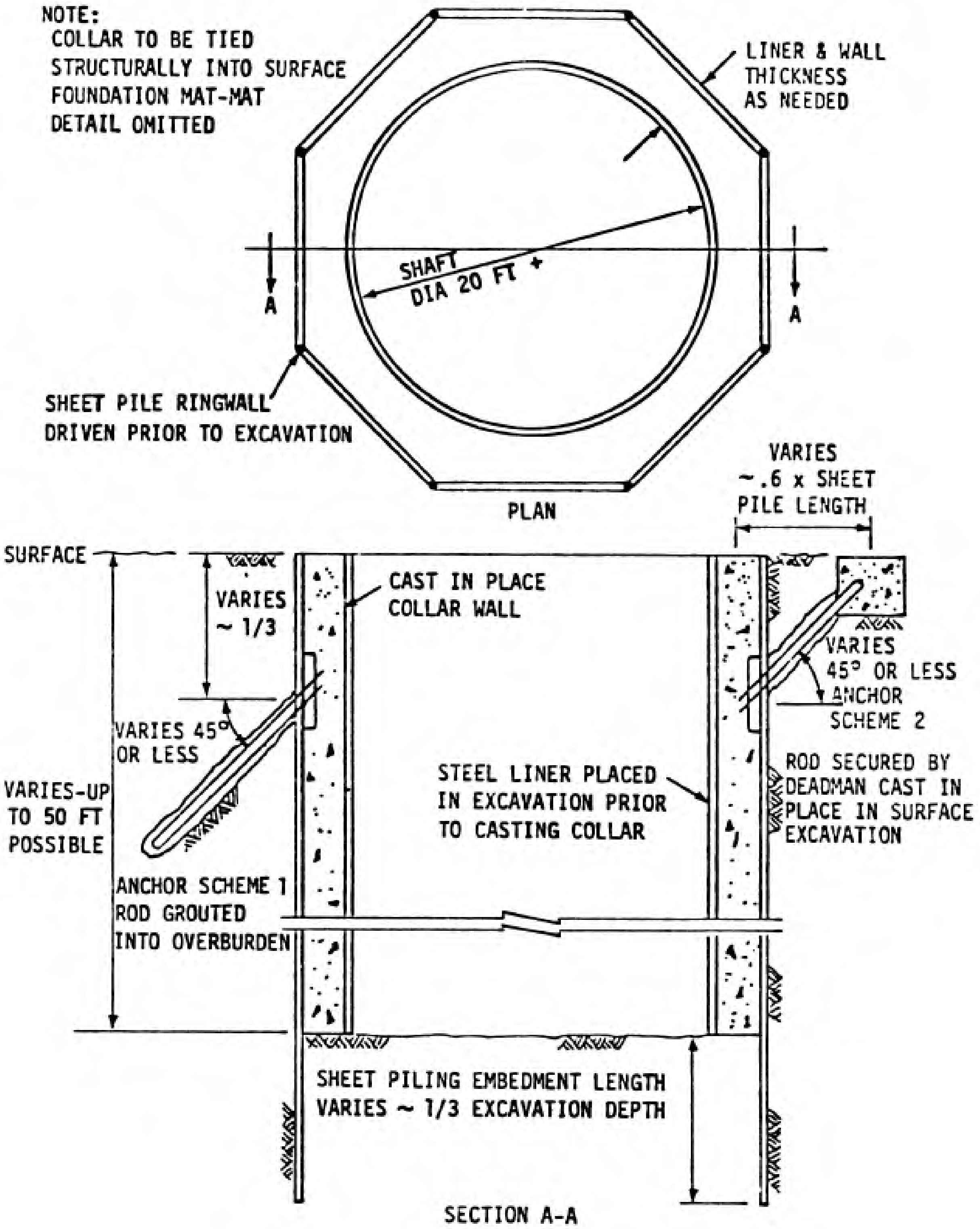


Figure 38. Cast-in-place shaft collar inside sheet pile ring wall

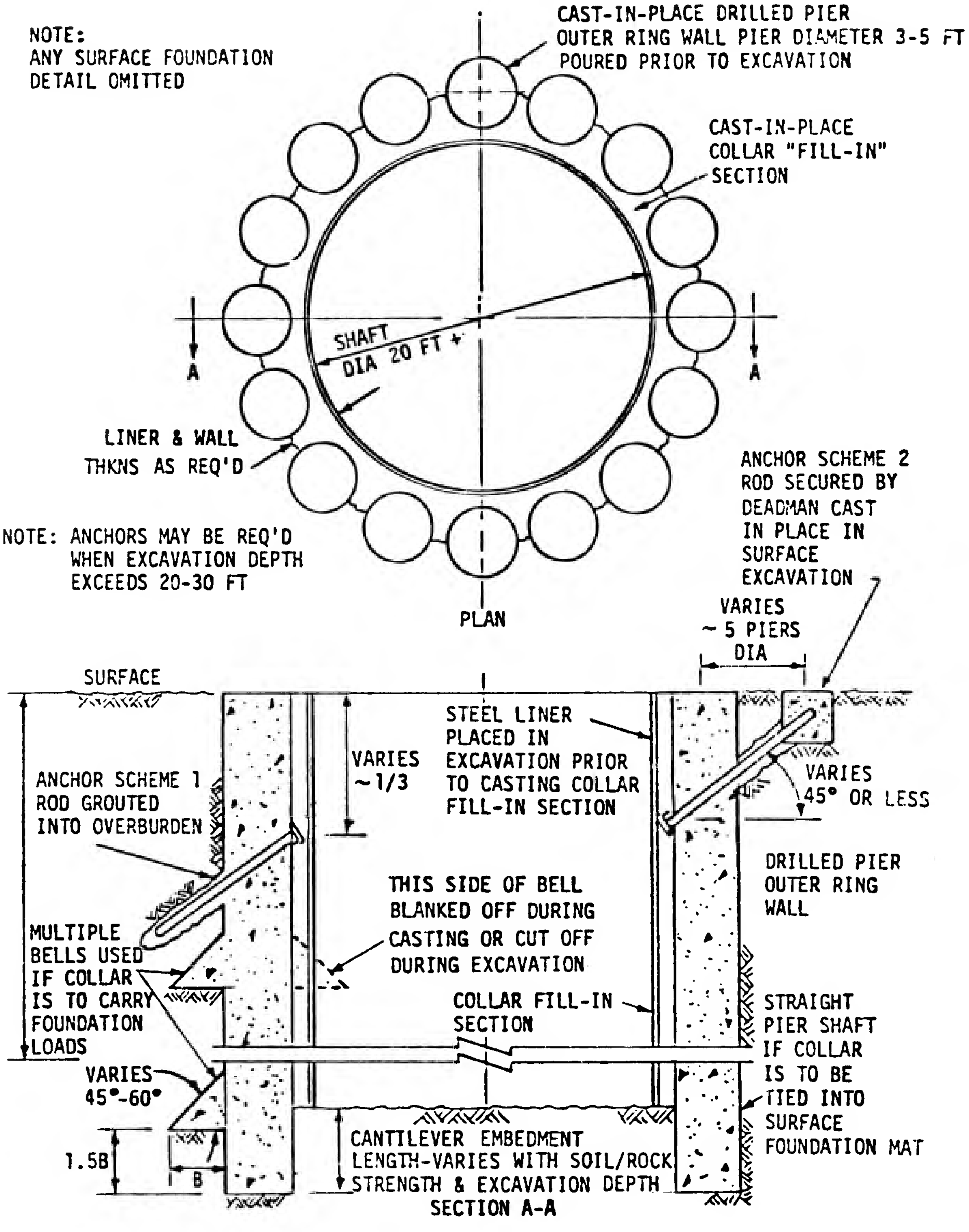


Figure 39. Cast-in-place shaft collar inside drilled pier ring wall

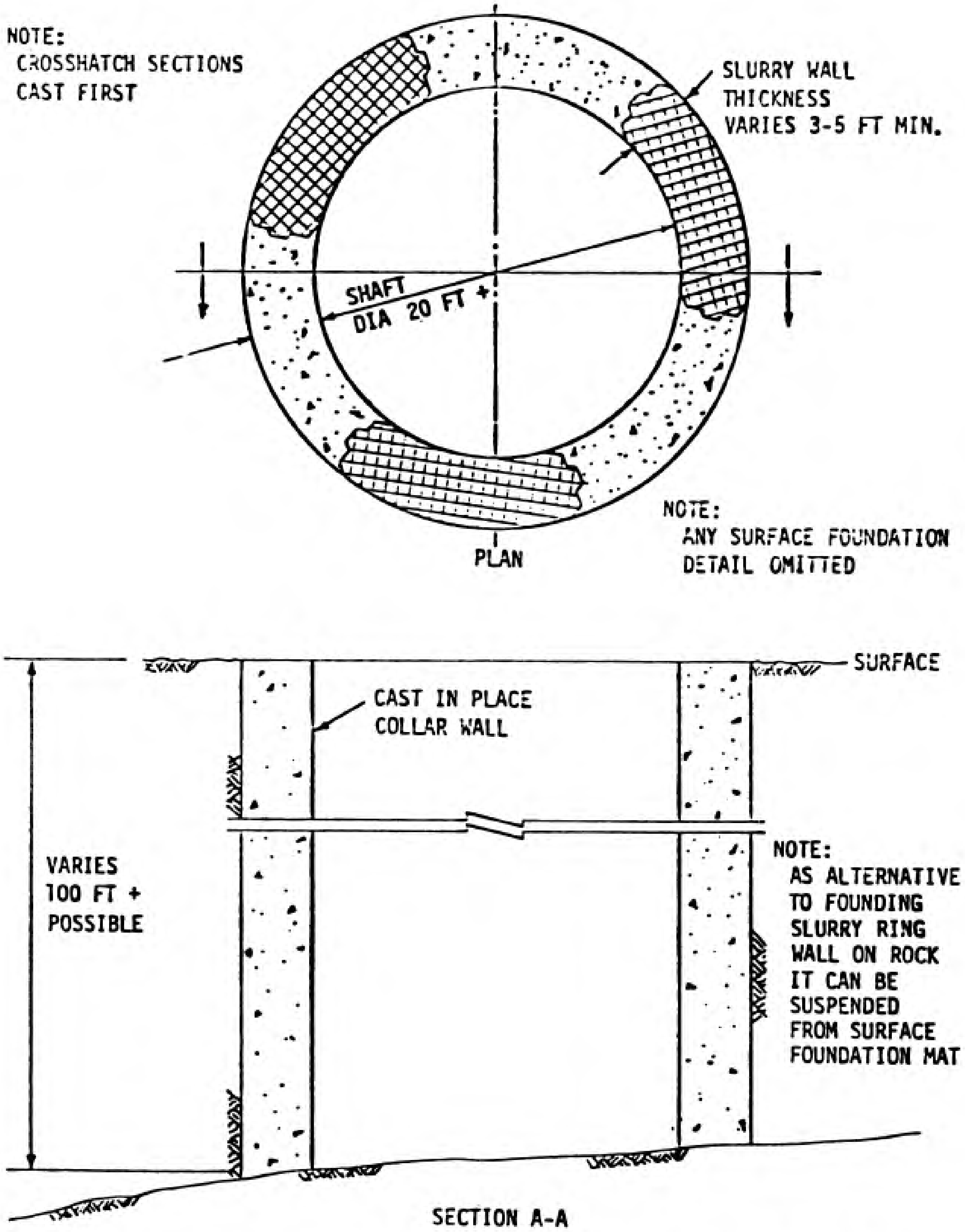


Figure 40. Cast-in-place shaft collar inside slurry trench ring wall

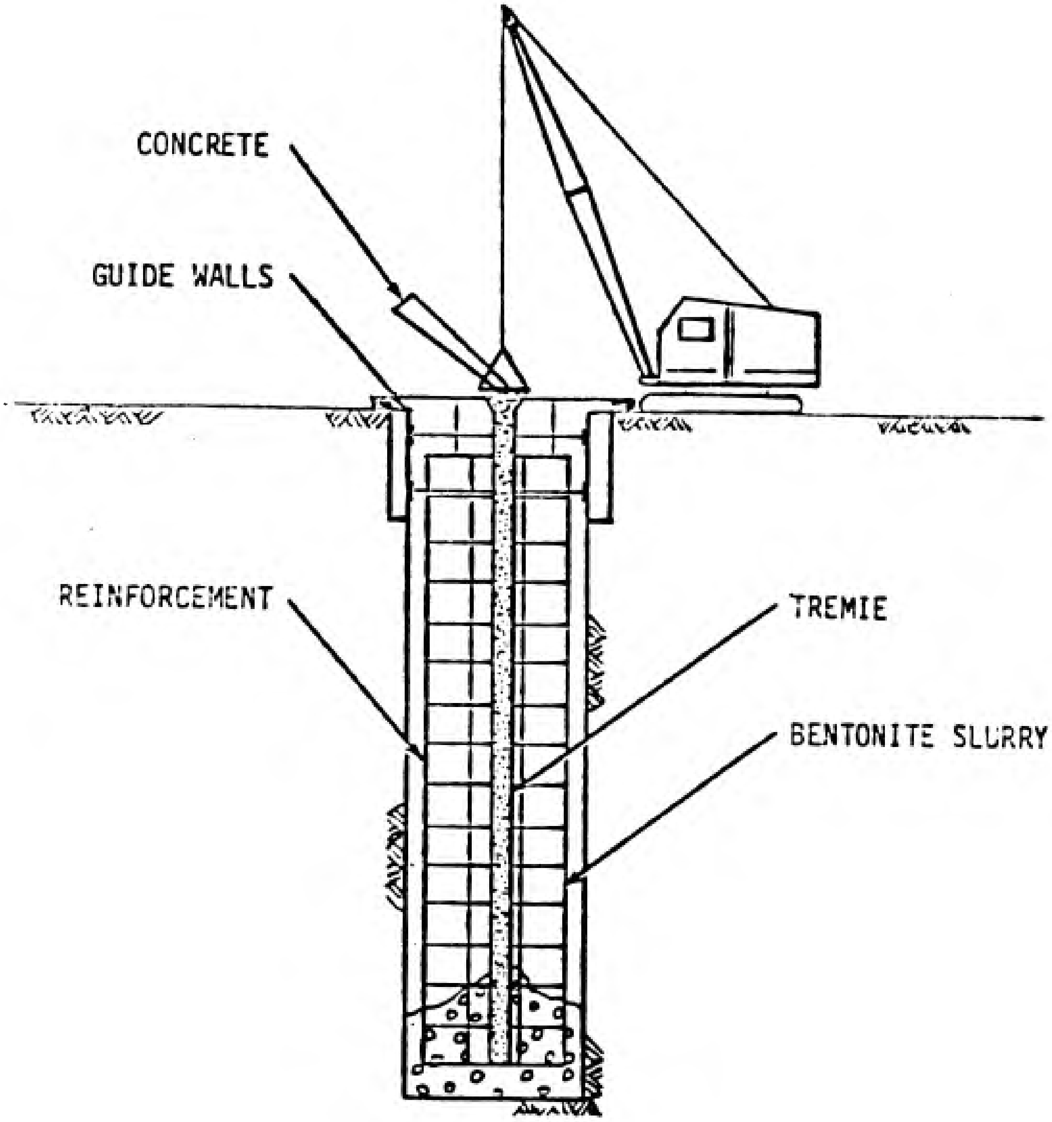


Figure 41. Sketch illustrating construction by the slurry trench method

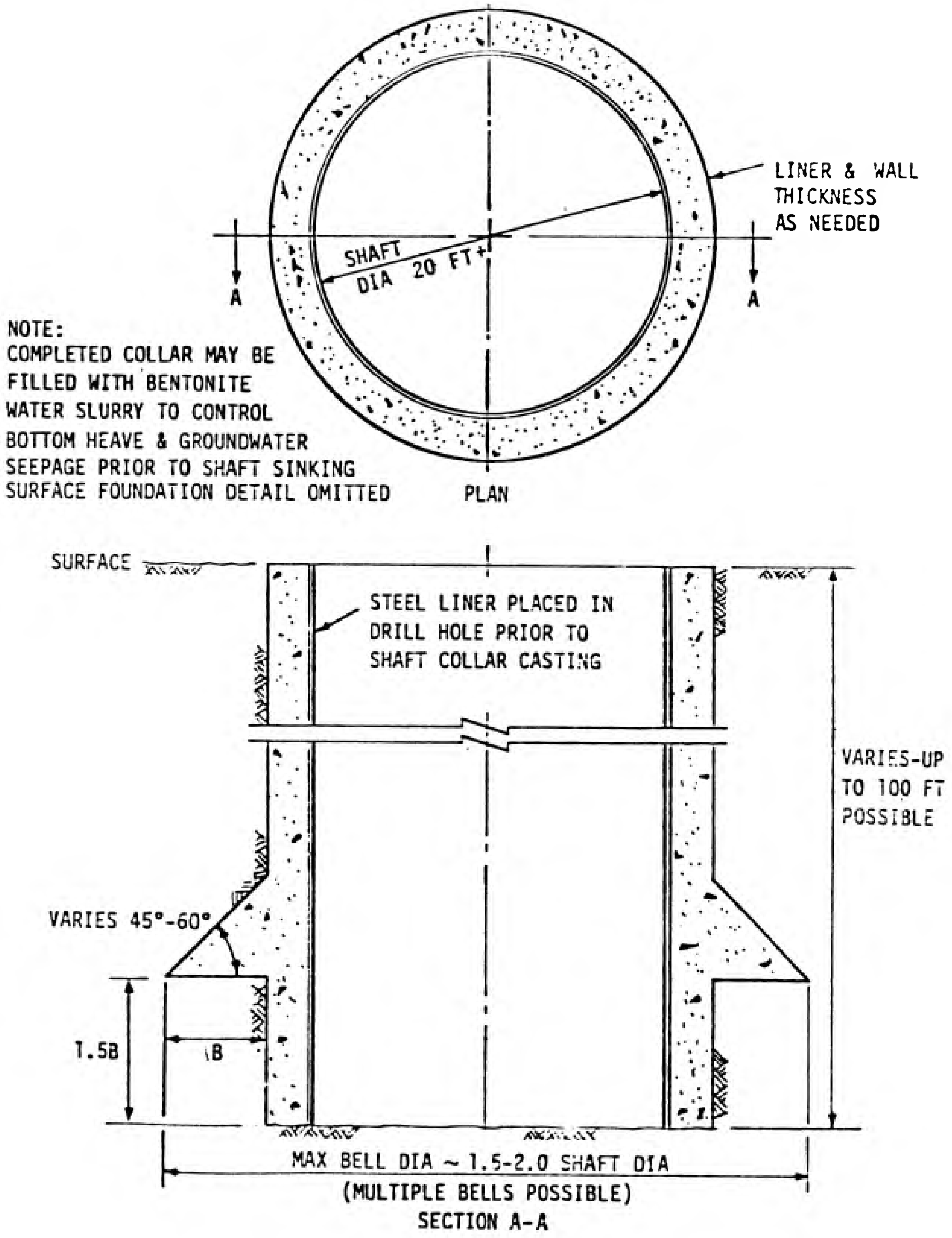


Figure 42. Drilled and cast-in-place shaft collar (inside large-diameter drilled pier)

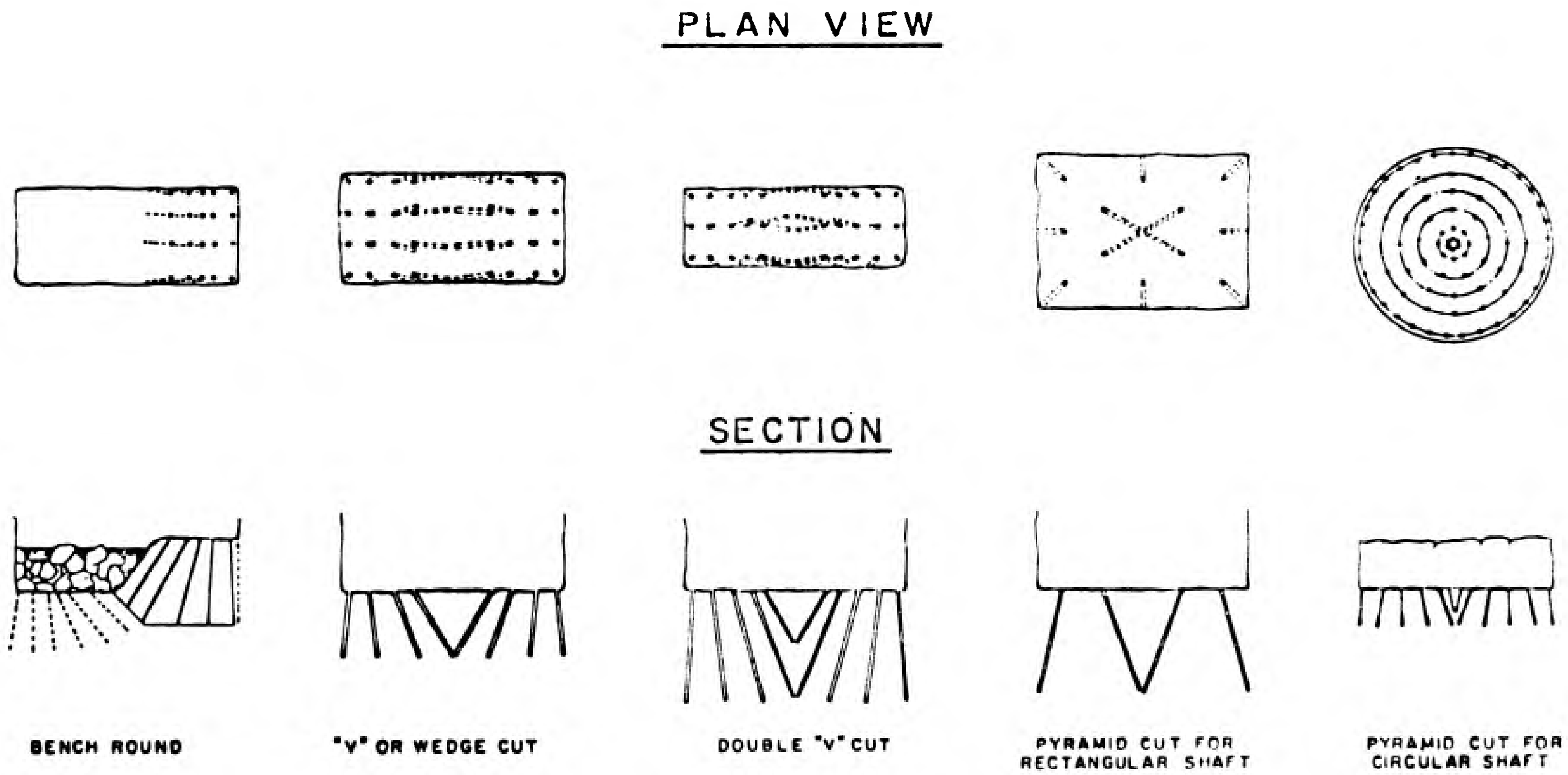


Figure 43. Blasting patterns (after Stevens, 1973)

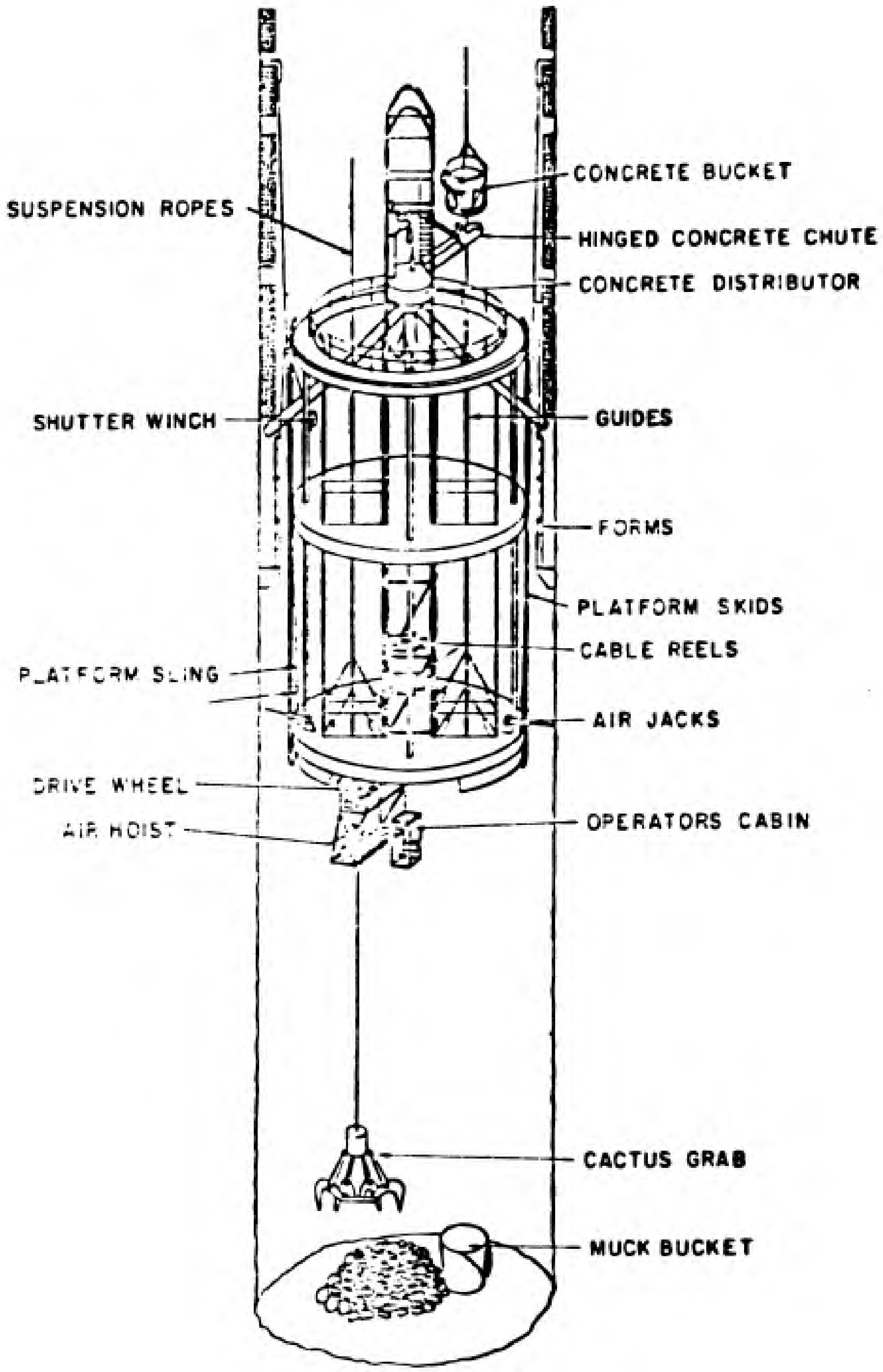


Figure 44. Multideck stage (after Jamieson, Pearse, and Plumstead, 1961)

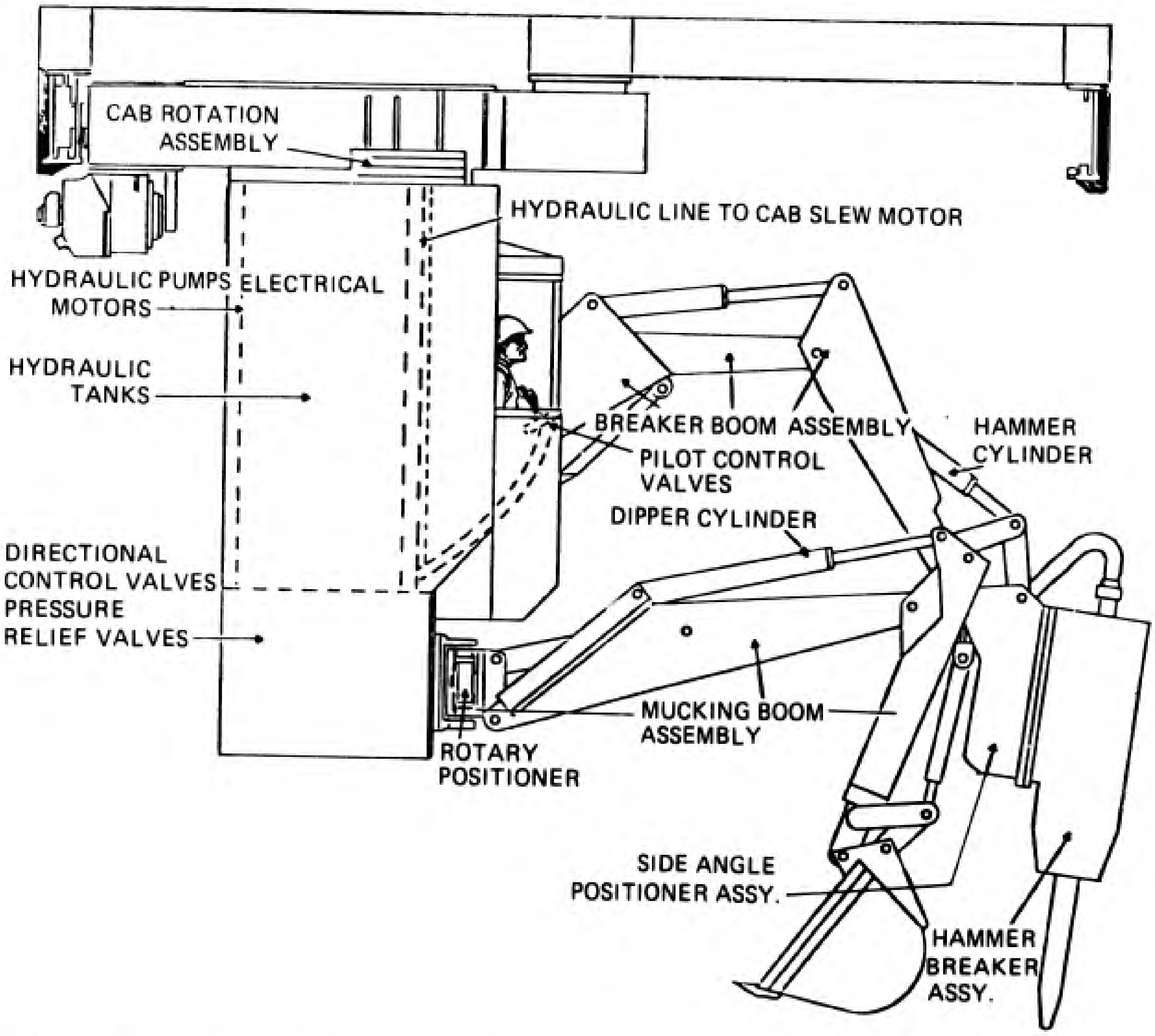


Figure 45. General arrangement of major hydraulic components of impactor

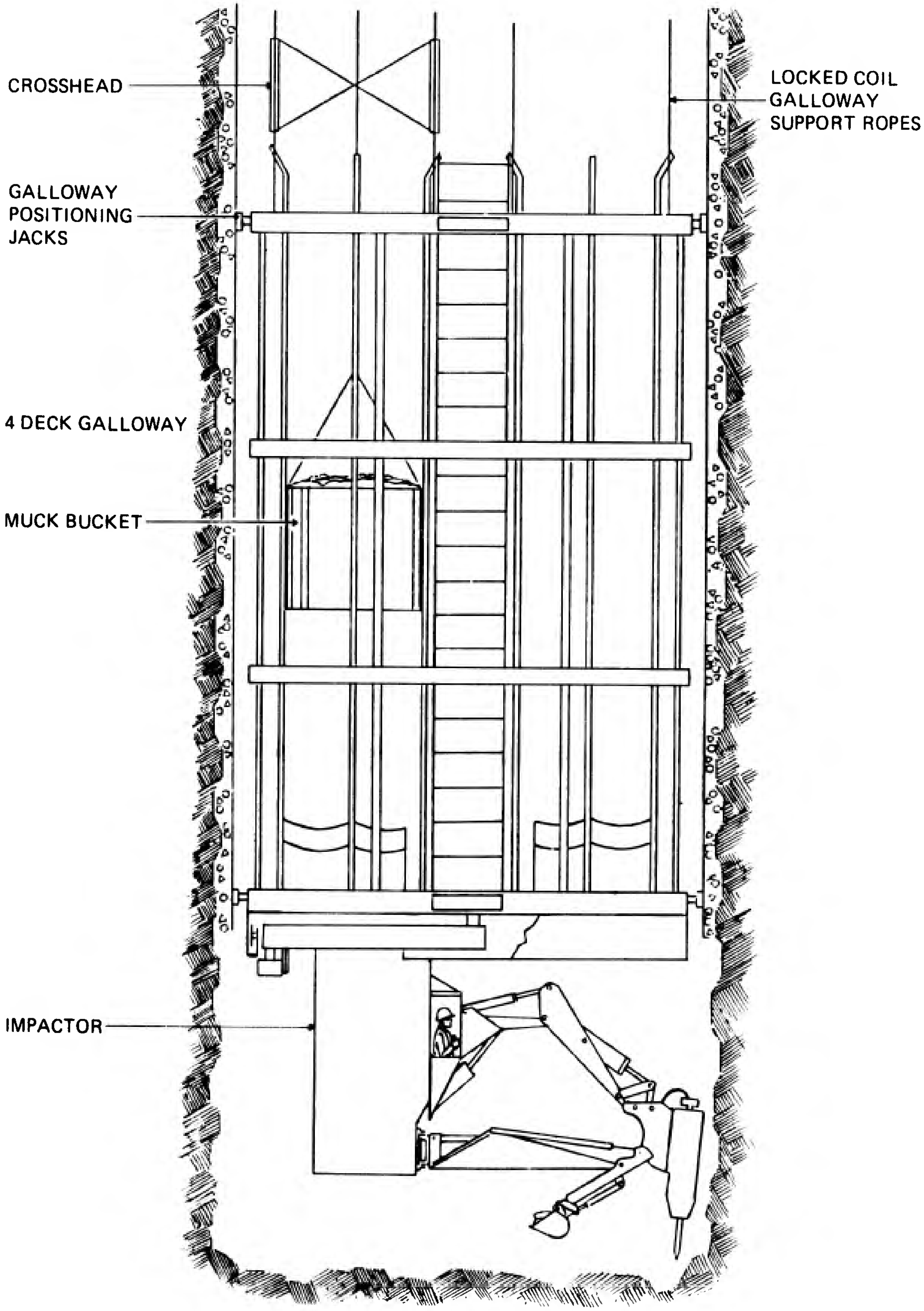


Figure 46. General arrangement of the galloway and impactor

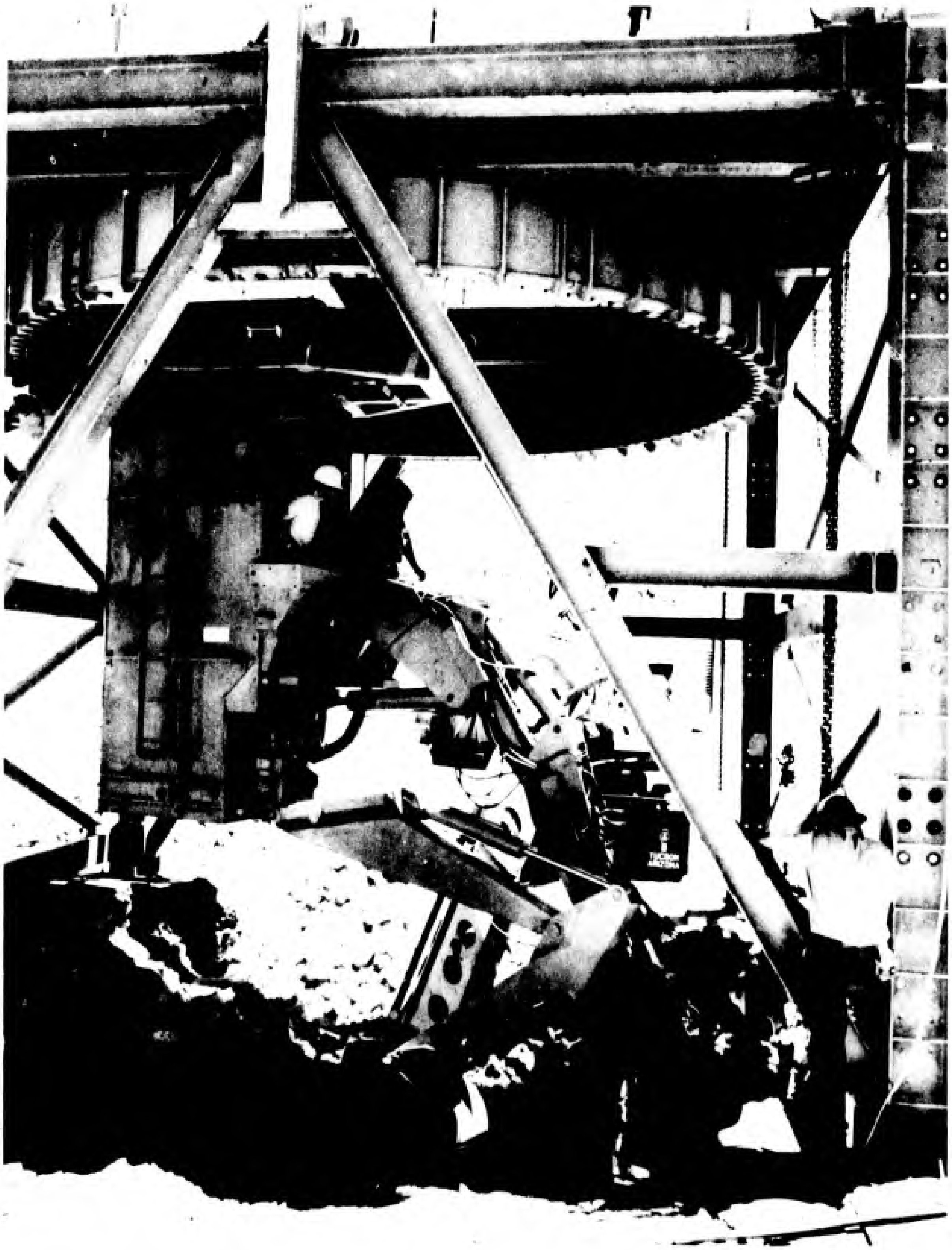


Figure 47. Impactor shaft sinker

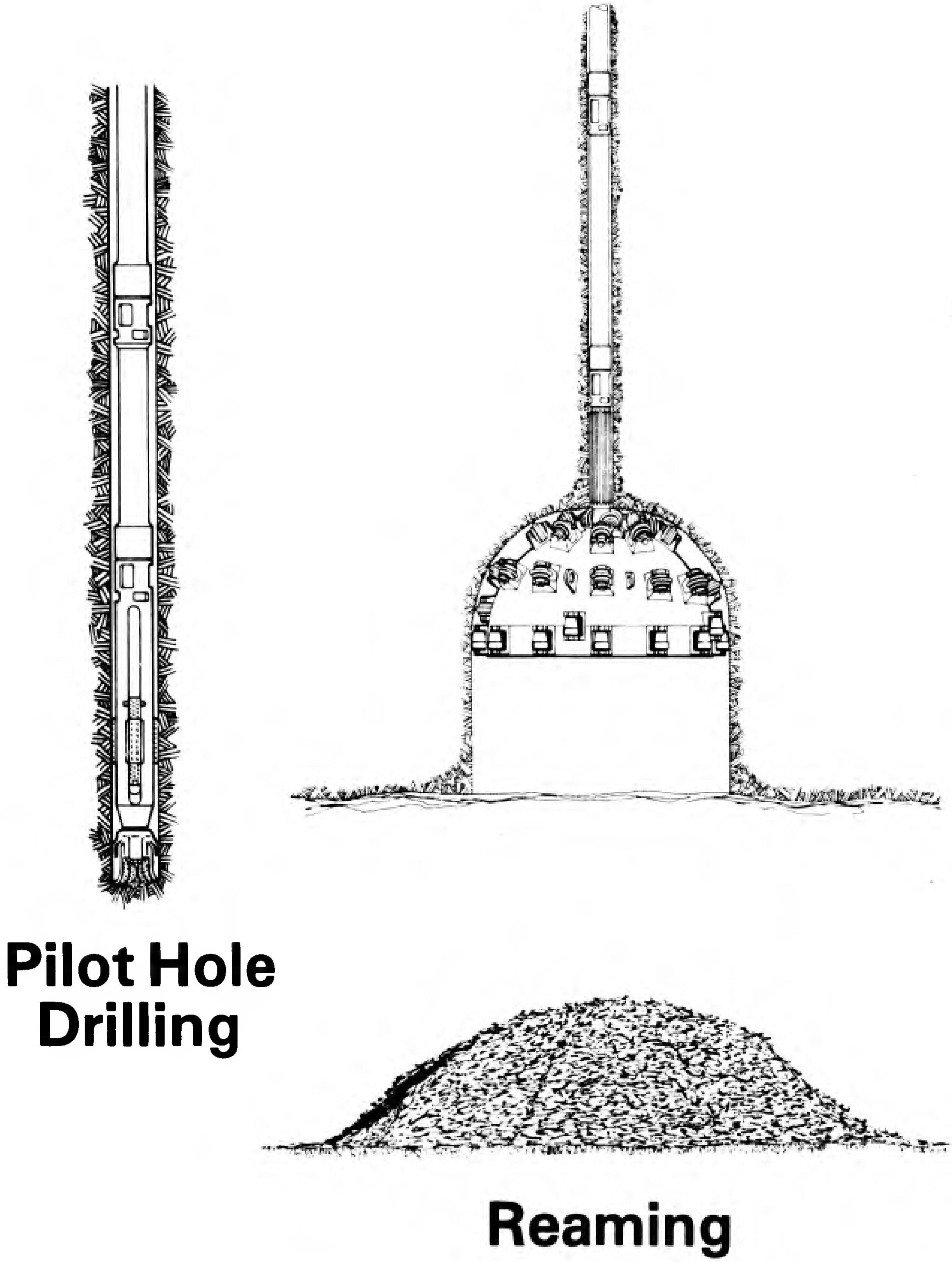


Figure 48. Principle of raise boring

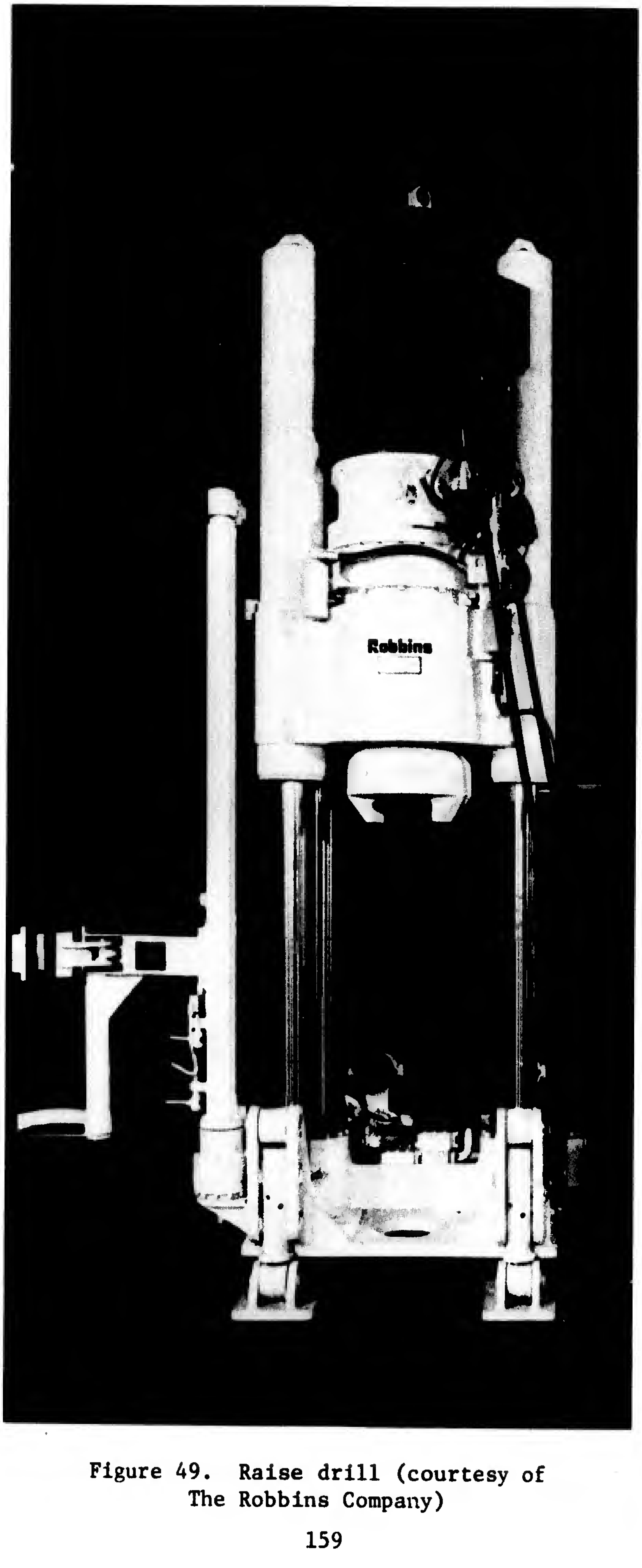


Figure 49. Raise drill (courtesy of The Robbins Company)

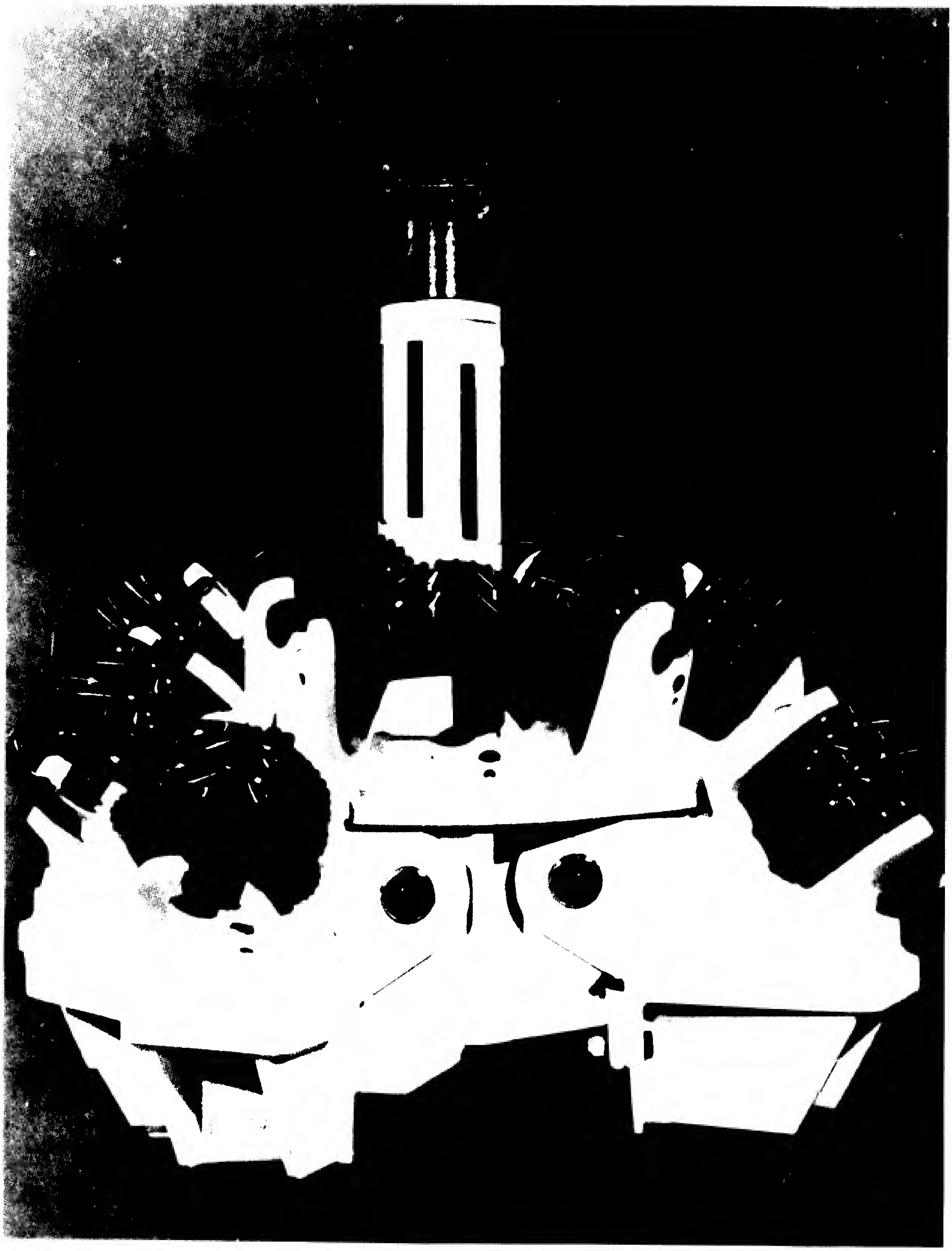


Figure 50. Raise-bore cutterhead and bits (courtesy of Robbins Co.)

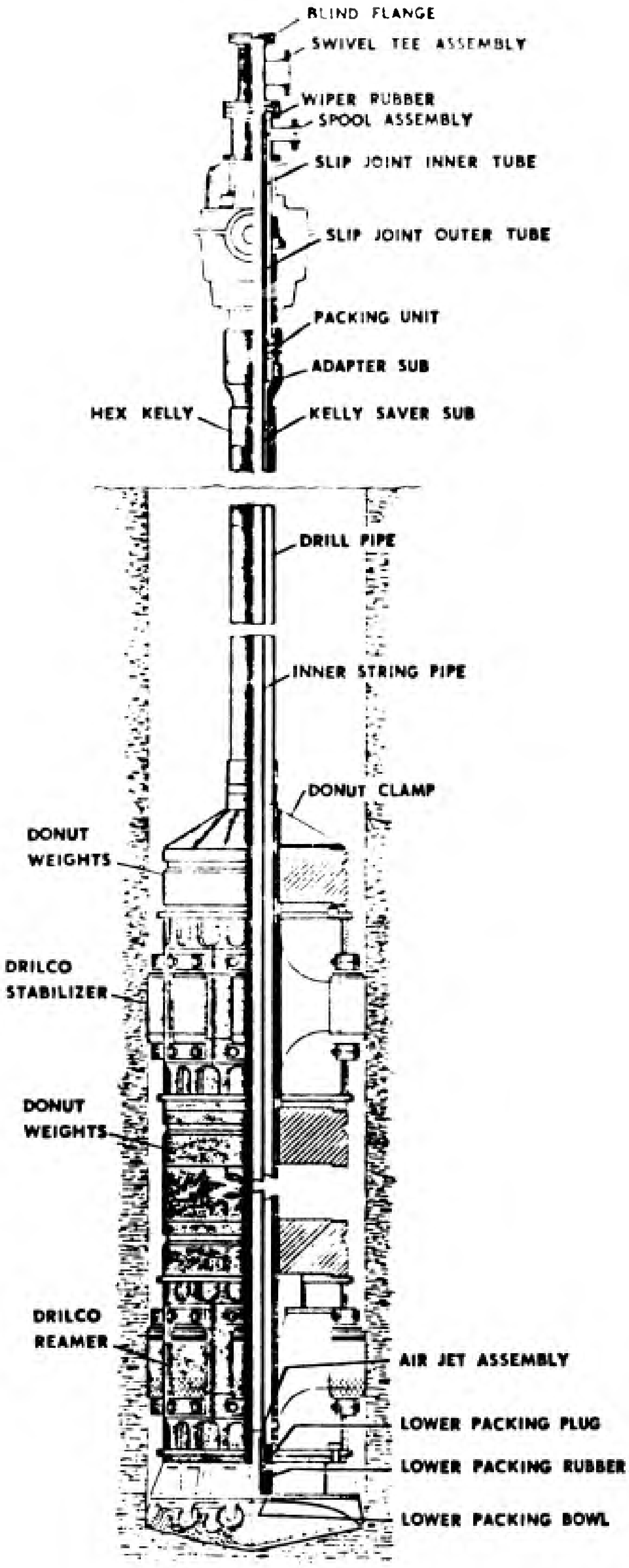


Figure 51. Typical drill-string assembly for drilling large-diameter shafts

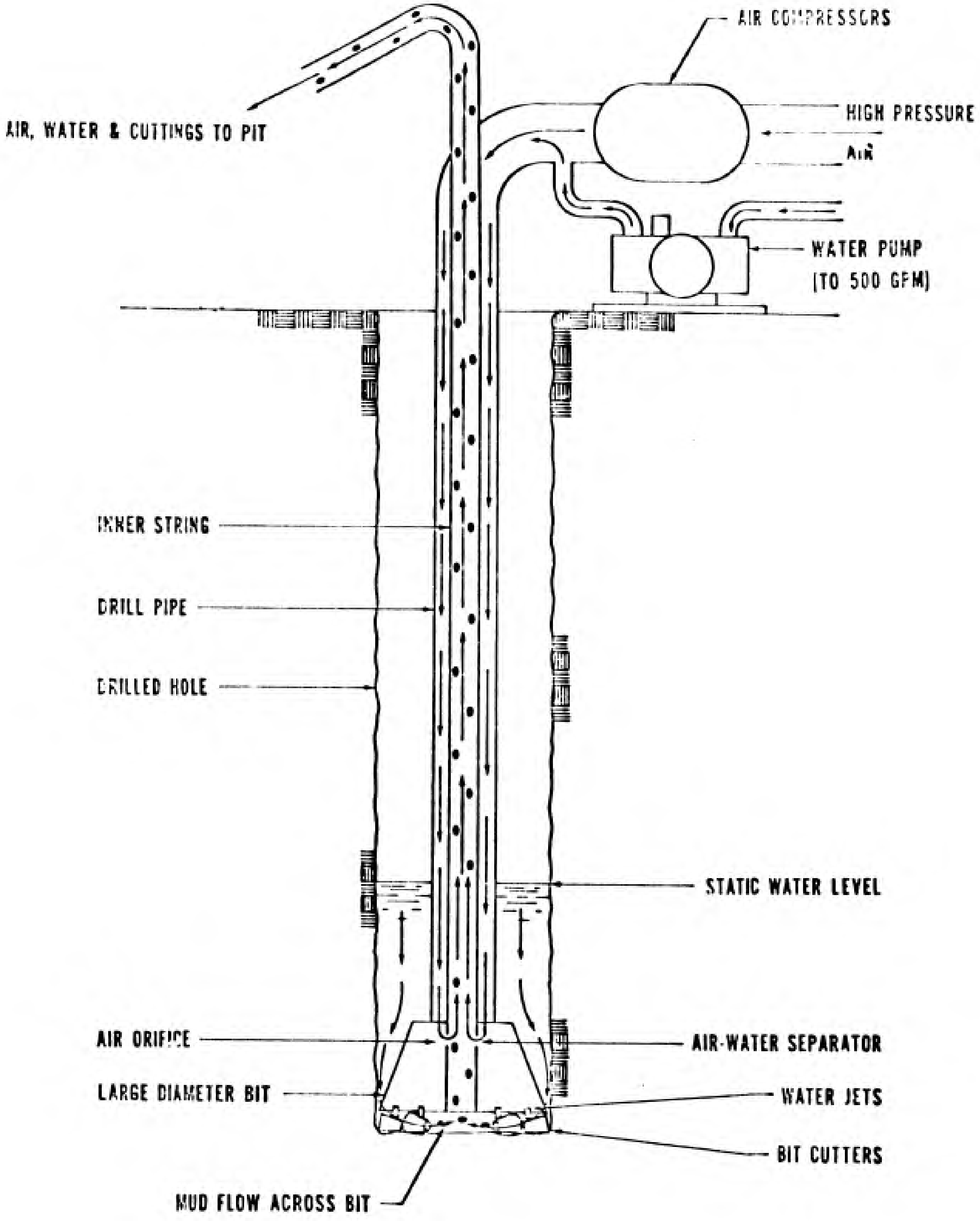


Figure 52. Dual string air-water jet bit circulating system

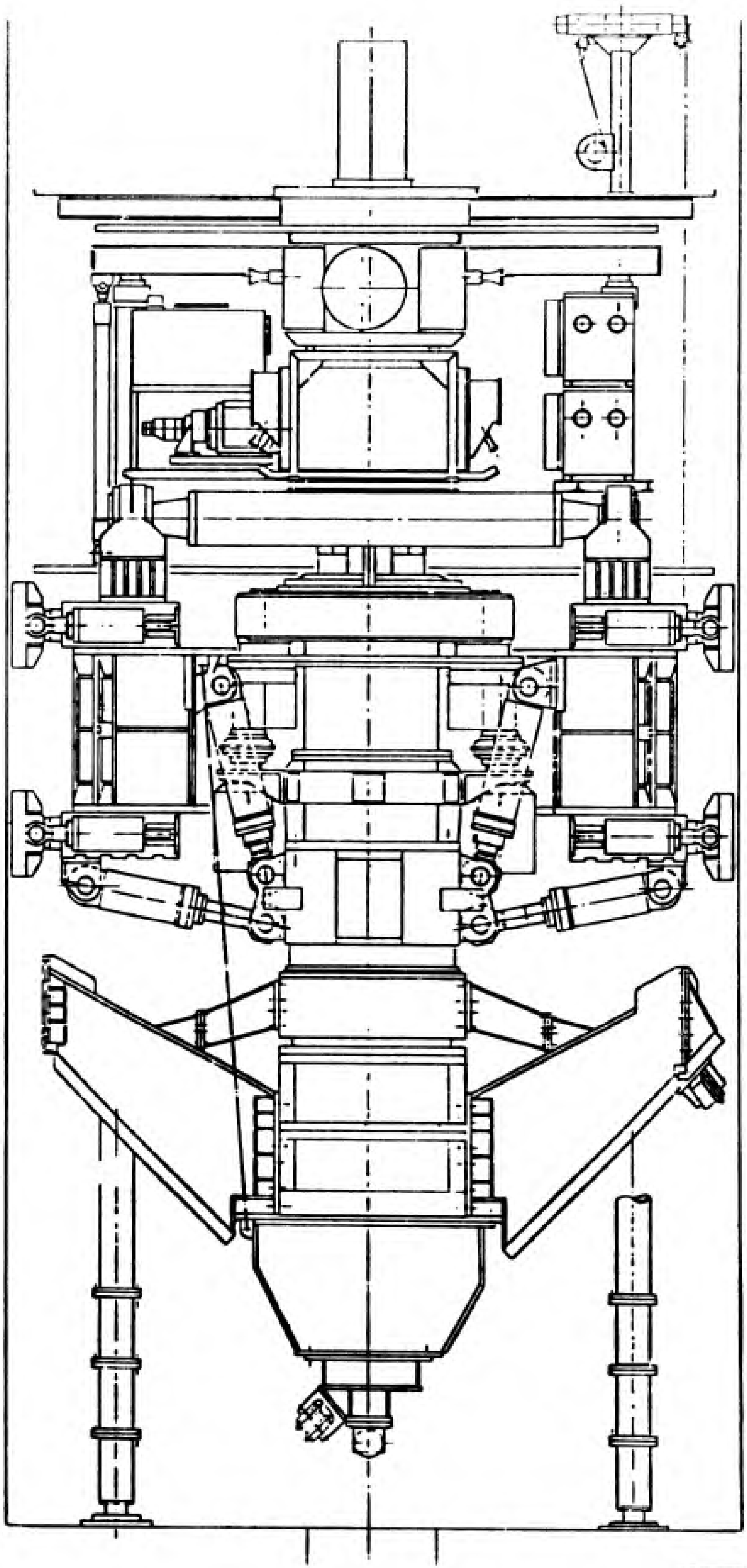


Figure 53. Wirth V-mole reamer

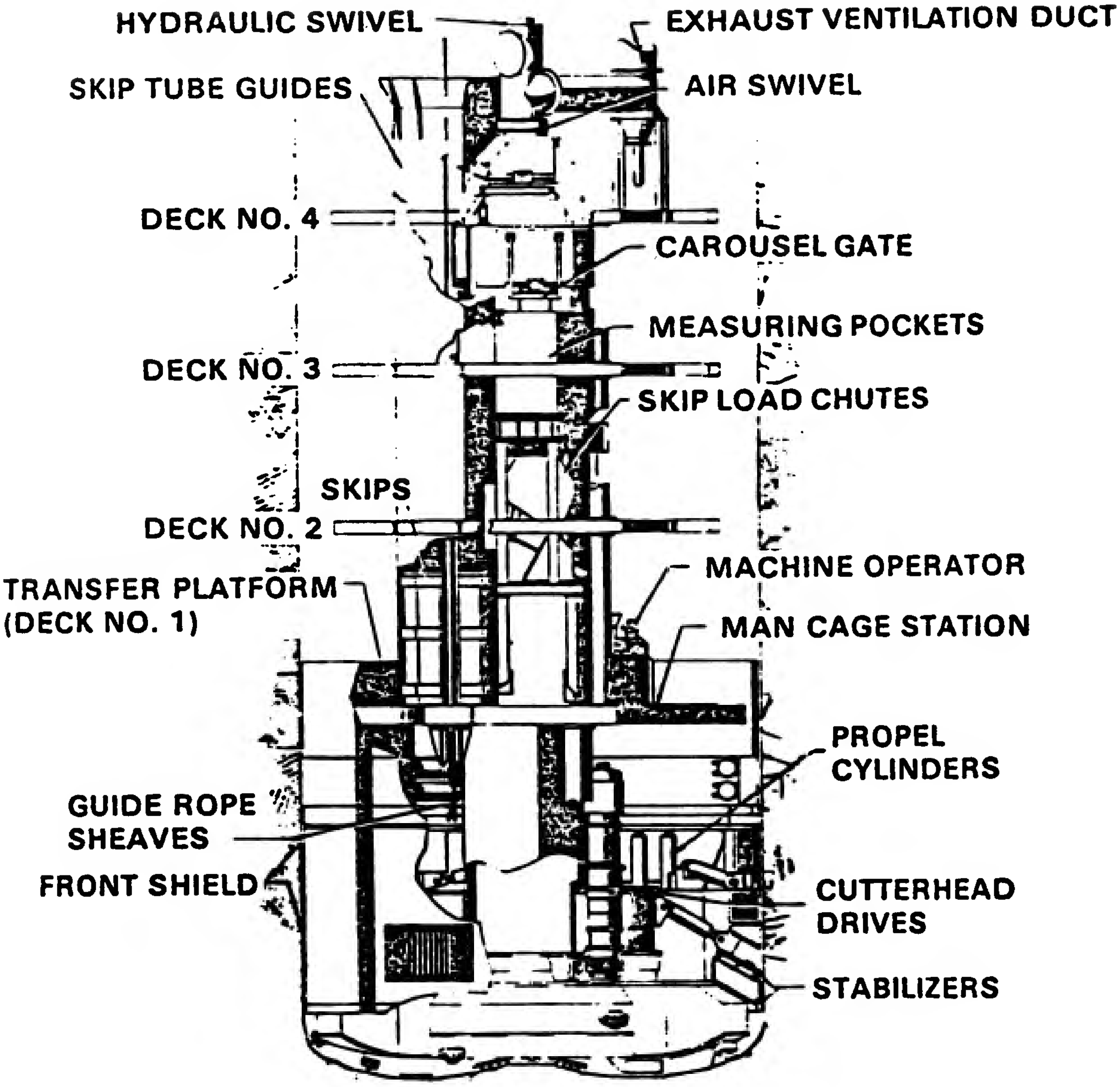


Figure 54. Blind shaft borer

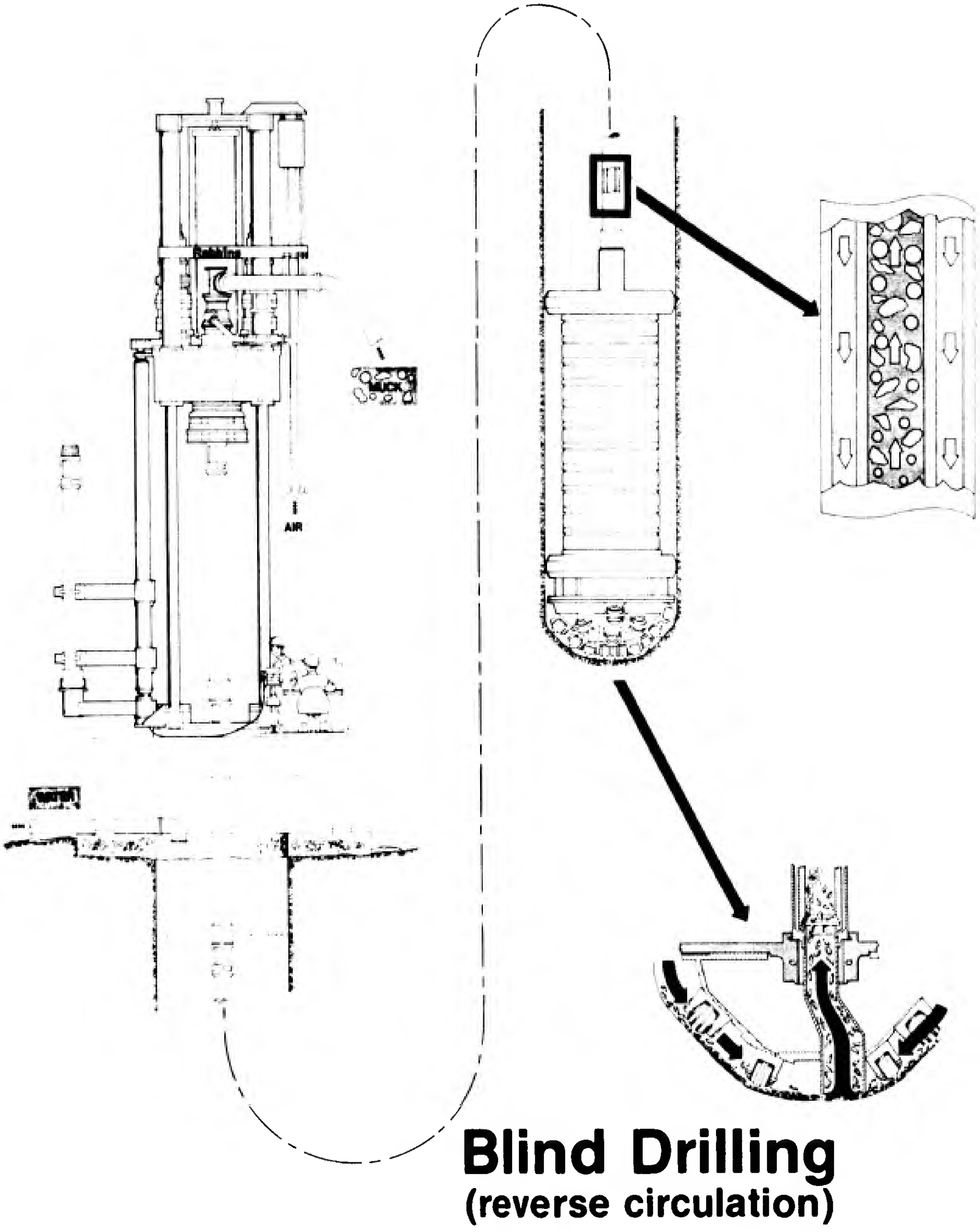


Figure 55. Blind shaft borer equipped with pneumatic muck hoisting system

PART IV: MUCK HANDLING METHODS AND EQUIPMENT

328. Muck handling includes the loading, hauling, and disposal of soil and rock debris created by the tunnel and shaft excavation operations. Muck handling systems (methods and equipment) that are presently used or have potential for use in construction of deep tunnels and shafts in rock are described in this section. There are three commonly used methods for removal of tunnel muck, based on the mode of transport.

a. Rail-mounted muck trains.

b. Rubber-tired and crawler-mounted mucking equipment.

c. Conveyor systems.

329. In addition, recent research (Powell and Ruby, 1981; Faddick and Martin, 1974, 1977a and b, and 1978; Duncan, Tierney, and Schneider, 1970; and Duncan et al., 1979) backed up by limited actual tunnel experience (Chrysanthou, 1970, Dahl and McCain, 1974, Nelson et al., 1975, Miller et al., 1977, and Goedde, 1980) has indicated that other innovative systems may have potential for muck handling. These are the pneumatic and slurry pipeline methods.

330. Purchase, installation, and operation of a muck handling system can account for 15 to 20 percent of the cost of excavation (Scaravillo, 1977), so developing an efficient system can save significant amounts of money.

331. Many important factors must be balanced to develop an efficient muck handling system. The system must be compatible with the excavation method used, so material characteristics (particle size and moisture), required handling rates, and whether a cyclic or continuous system is required must be considered. Tunnel geometry (length, width, height, shape, and slope), track or road bed stability, and site conditions may impose additional constraints. The longer the drive and smaller the cross section, the more likely it is that muck handling will set the overall pace for the drive; i.e., the material cannot be removed as fast as it is excavated. Power requirements and options must also be considered, as well as system capital costs, reliability, maintainability, availability, and other factors. These factors are discussed in the following paragraphs on specific muck handling methods and equipment.

Rail-Mounted Muck Trains

332. Rail-mounted muck trains have been extensively used for more than a century and still move a large share of the tunnel muck and mine ore excavated each year in the United States and worldwide. Rail muck trains are quite reliable and can achieve high muck removal rates by adding more or larger cars and locomotives. Mobilization time, capital costs, and installation costs are higher for rail systems than for trucks but for large projects, rail train systems usually are more economical over the long haul because of their high capacity and durability and resale value. Trains which travel at 3 to 12 mph loaded, are slower than trucks which can reach 30 mph, but capacities are much higher for trains. So both haul times and capacities must be checked against the rate of muck production to ensure sufficient peak capacity, regardless of the mucking system chosen. Maximum recommended grade for rail systems is about 3 percent, and optimum grade is 0-1 percent. If a winch system is used, this grade restriction does not apply. The system consists of locomotives, cars, track, switches, and loading and unloading units. These components are described in the following paragraphs.

Loading

333. TBM's and many roadheaders contain their own conveyor belts to transport the muck from the tunnel face to the muck cars. Drill and blast driven tunnels require the use of a special muck loader, such as the Conway Mucker manufactured by the Goodman Equipment Corporation as shown in Appendix A. Muck loaders use a bucket or arms to load the muck onto a conveyor belt which then loads the muck cars.

334. With drill and blast excavation, the cars may be loaded individually. However, individual car loading is undesirable in continuous excavation systems, because the excavation must be stopped or the muck must be stockpiled while the loaded car is exchanged for an empty car.

335. For any excavation method, the muck may be continuously loaded into a train in one of three ways: (a) train loading conveyor belt (Figure 56a), (b) slusher scraper (Figure 56b), or (c) conveyor belt cars. If muck is available, the entire train may be loaded without stopping.

336. The conveyor belt system consists of a conveyor mounted on a rigid frame with wheels that are of wider gage than the train track. This allows the empty train to back under the long conveyor frame. The muck is fed from

the conveyor belt to the first muck car behind the locomotive. As the car is filled the train moves forward slowly. This sequence is continued until all the cars on the train are loaded.

337. The slusher scraper is a hoe or box type scraper that operates in a trough erected on top of and between the cars. The trough is constructed with a closed bottom between the cars and an open bottom over the cars. The lead car in the train is loaded by a mucking machine and as the muck builds up in this car it is pulled back by the scraper to load the other cars in the train. To use this train loading method, the muck should be finely broken to permit efficient scraper operation and the scraper should have enough capacity to keep up with the mucker. This train loading system has been used successfully with all sizes of cars, but it has been most successful with small cars used in small-diameter tunnels where rock was broken into small pieces.

338. Conveyor belt trains consist of articulated cars with a conveyor belt forming the bottom of the train. The loading procedure is to load the end car in the train with a mucker; the belt then moves the muck up the length of the train. The train is unloaded by reversing the belt.

Hauling

339. Rail-mounted muck hauling equipment includes locomotives, muck cars, track, and switches.

340. Locomotives. There are several types of locomotives distinguished mainly by their source of power. The locomotives used for tunneling are battery powered, diesel, and direct current battery supplemental trollies. Within each type of locomotive there are various lengths, widths, heights, and horsepower ratings. Choosing the right locomotive is a function of tunnel dimension, load requirement, capital cost, reliability, availability, maintainability, and ventilation requirements.

341. The following guidelines for selection of the right locomotive for a particular tunneling job were discussed in detail by Parker (1970) quoted herein by permission of the publisher: McGraw-Hill.

342. "Preliminary selection of a locomotive can be made by determination of the weight of the locomotive required to provide traction, the maximum horsepower required to accelerate the loaded train to a reasonable speed, and the continuous horsepower required to maintain this speed. If long stretches of haulage are on steep grades, careful consideration must also be given to braking requirements. If battery locomotives are being considered, frequency

of battery recharging must be determined. In every case, final equipment selection should be governed by the guaranteed characteristics stated on the manufacturer's specification sheets, with due consideration of probable loss of efficiency as the equipment ages.

343. "The tractive effort that can be exerted by a locomotive is a function of locomotive weight and of the coefficient of friction between the steel wheels and the steel rails. Although the coefficient of friction decreases as locomotive speed increases, the decrease is not significant in the ordinary range of tunnel haulage speeds. The coefficient of friction varies from 0.15 for wet, slick track to 0.25 for dry track. The tractive force which a given locomotive can exert is stated as

$$T = W_L F \tag{1}$$

where

T = tractive effort, lb
W_L = locomotive weight, lb
F = coefficient of friction

The tractive effort required of a locomotive is a function of the weight of the train (including the locomotive) and of the resistance to be overcome. The resistance to be overcome is composed of:

<u>a</u>. Rolling resistance is caused by the deformation of rails and wheels under the weight carried by the wheels. For steel wheels on steel rails, this is approximately 20 lb/ton of train weight.

<u>b</u>. Grade resistance is the force which must be overcome in lifting the weight of the train on an uphill grade. On downhill grades, grade resistance is a negative quantity. Grade resistance is approximately 20 lb/ton of train weight per 1 percent of grade.

<u>c</u>. Acceleration resistance is the force required to accelerate the train. It is a function of the rate of acceleration. It amounts to 90 lb/ton of train weight per mph per sec. Usual acceleration rates in tunnel service are in the range of 0.1 to 0.2 mph per sec.

344. "The tractive effort required of a locomotive may be greater to return a string of empty cars upgrade than to move loaded cars downgrade, but it will frequently be necessary in any tunnel to move loaded trains in either direction during switching, train makeup, and other operations, and locomotives should be selected on this basis.

345. "The required tractive effort for a given train during acceleration can be stated as

$$T_T = \frac{(NW_C + W_L)(R_R + R_G + R_A)}{2{,}000}$$

where

T_T = total tractive effort, lb
N = number of cars
W_C = gross weight of 1 car, lb
W_L = weight of locomotive, lb
R_R = rolling resistance, lb/ton
R_G = grade resistance, lb/ton
R_A = acceleration resistance, lb/ton

This is restated for use as

$$T_T = (NW_C1 + W_L1)(20 + 20G + 90A) \tag{2}$$

where

W_C1 = gross weight of 1 car, tons
W_L1 = locomotive weight, tons
G = grade, percent
A = acceleration, mph

The required tractive effort after acceleration is stated

$$T = (NW_C1 + W_L1)(20 + 20G) \tag{3}$$

346. "The foregoing remarks and formulas pertain only to the weight requirements for locomotives. The second factor in selecting a locomotive, whether diesel or electric, is the peak power requirement for accelerating the train. The formula is derived in many texts from mechanics and is stated as

$$P_P = \frac{T_T S}{375E} \tag{4}$$

where

P_P = required peak power, hp
E = efficiency of locomotive
S = speed after acceleration, mph

347. "The final factor applicable to all types of locomotives is the sustained power requirement necessary to keep the train moving at a constant speed. This is considered separately because diesel engines and electric motors are not capable of delivering power continuously at peak output. Attempting it will cause early failure of locomotive components.

348. "The required continuous power is stated as

$$P_C = \frac{T_R S}{375E} \qquad (5)$$

where

P_C = required continuous power, hp

T_R = tractive effort for rolling resistance and grade resistance applied to train weight

E = efficiency of locomotive

S = speed, mph

349. "Equations 1-5 are adequate to determine the power and weight requirements for locomotives."

350. From the known tunnel diameter, slope, and muck density, the acceleration, coefficient of friction, and speed of the train are determined and a trial locomotive may be chosen based on the estimated horsepower requirements. The tractive effort available and required are calculated for the locomotive selected. The number of cars, N , is chosen sufficiently large to haul the muck from one advance by drill and blast or one cycle of TBM advance. If the required tractive effort, T_T , is larger than the available tractive effort, T , then a larger locomotive is chosen and the procedure is repeated until $T_T \leq T$. The required peak power, P_P , and the required continuous power, P_C , are then calculated to insure that the locomotive chosen is within the power requirements.

351. The choice between battery, diesel, or direct current battery supplemental trolley locomotives is based on maintenance, length of haul, cost, availability, and reliability. In past years the battery powered trains were the workhorse of the tunnel. These units have good availability, high resale value, and result in lower ventilation requirements than the diesel. Today, the diesel locomotives have made it possible to increase speed, reduce the number of locomotives required and eliminate battery maintenance and dangerous direct current trolley wires in the tunnel. However, ventilation

requirements are larger and scrubbers have to be installed on diesel locomotives.

352. The manufacturers of locomotives provide the necessary specifications for locomotive selection. An example of this data may be found in Appendix A along with a list of locomotive manufacturers.

353. Muck cars. The main types of mucking cars, distinguished by their mode of dumping, are (a) side dumping, (b) bottom dumping, and (c) cars which require assistance in dumping. One other type is the conveyor belt car.

354. Cars requiring assistance in dumping are emptied by one of three methods, side dump (SD), center rotary dump (CRD), or rotary dump (RD). Figure 57 shows a 5-car rotary dumper. The side dump cars are unloaded by hydraulic or air cylinders mounted on the side of the car. The car is brought alongside the jack, the side of the car is lifted and the muck is dumped while the wheels and frame remain attached to the rest of the train. The jack and body of the car are lowered, the train is pulled forward, and this sequence is repeated for each of the remaining cars. The SD car is probably the most commonly used muck car in tunneling. The SD has low side height and large muck capacity.

355. Other nonself dumping muck cars are built with the body or box connected to the frame with no hinges or bottom dump doors. The train is pulled through a cylinder with tracks arranged so that the hitches at each end of the muck car are aligned along the center of the cylinder. The cylinder is mounted on rollers connected to a motor. When the car is positioned correctly, the cylinder is rotated nearly 180 degrees and the muck falls through the open slot in the cylinder. The CRD is unloaded in the same manner, except the CRD must be centered along the axis of the cylinder and the hitch swivel. The RD hitch does not swivel nor is it aligned along the center line of the cylinder.

356. The side dumping car, self dumper, operates just as its name implies. To dump the load a latch is released, the side opens, and an air cylinder on the car tilts the body to dump the muck. The cost of dumping mechanisms limits the use of this type of dumper, especially in small tunnels. Where size is not a problem this technique is used more often, as in the 70- to 100-ton range. Small to medium diameter tunnels have cars from 5- to 20-ton capacity (Difco, Inc.).

357. Increased use of TBM excavation has resulted in new emphasis on reducing dumping time. Consequently, bottom dumping cars have increased in

use because they are easily adapted to automatic dumping. The bottom dump car depends on gravity for dumping its load. As the car is pulled over a dumping floor, a lever is tripped, the door of the car folds down, and muck is dumped. After dumping the car is pulled over a raised obstruction and the door closes automatically.

358. The new automatic dumping systems have been able to keep up with the increase in TBM excavation rate. A 3.15-m-diam tunnel near Salzburg, Austria, was driven using a Series 120 TBM by Robbins and Company. The mucking system by Envil Lechner, Inc., was able to keep up with a maximum excavation rate of 47 m/day, or 16.7 m^3/hr. Nine cars of 5-m^3 capacity moved continuously at 1 m/sec (2.25 mph) during the unloading cycle (Harding, 1980).

359. Automatic dump car costs were discussed in Mining Engineering (1981). Automated rail haulage systems have been introduced in about six underground mines throughout the world. Under DOE contract, Booz, Allen, and Hamilton are developing an automated system for U. S. Coal Mines.

360. At the General Blumenthal mine in West Germany, ARHA has reduced haulage costs by 55 percent, manpower was reduced by 61 percent, and annual locomotive maintenance was reduced to about 3.5 percent of purchase price, compared to 25 percent for the manual system. Accidents and derailments were almost entirely eliminated.

361. Comparison of a rotary dump system and an automatic continuous dumping system is found in Mining Engineering (1980). The rotary system employs 7.9-m^3 boxcars. Three cars at a time are dumped by a rotating dumping mechanism which turns the cars upside down and returns them to an upright position after dumping is completed. These trains have 15 cars and an 18-ton rated trolley locomotive. It takes 6 min to dump 15 cars by this method.

362. The continuous dumping system utilizes equipment manufactured by ASEA of Sweden. The bottom dumping train was able to dump the 10-car train, pulled by an 18-ton locomotive, in 45 to 50 sec.

363. The advantages of the bottom dump were faster dumping, less maintenance of dumping equipment, and less personnel at the dumping station. The problems with bottom dump were that the ASEA cars are wider and higher than rotary cars and will not fit in many tunnels. Dirty floors cause alignment problems and even derailment because of the closeness of the car to the track, and the cars apply three times more bearing pressure per wheel than rotary cars resulting in shorter track life.

364. The main consideration in choosing a mucking car is the tunnel's dimensions. The widest cars that can pass each other in a tunnel should be selected in order to reduce the number of car changes required in mucking out a round. The mucker's ability to spread out the load in a car may restrict its length. In small tunnels it is difficult to place two cars abreast. To get around the problem a conveyor belt train may be chosen. These trains are composed of articulated cars with a conveyor belt forming the bottom of the train. The muck is loaded in the last car in the train, the belt then moves the muck up the length of the train. The belt in each car is stopped as the train car is filled. The train is unloaded by reversing the procedure. The major problems with conveyor trains are increased capital cost, availability, and maintainability.

365. Track. Train track is generally sold by the pound; different size track is rated by its cross-sectional dimensions and its weight. Dimensions, section modulus, weight per 100 ft of two rails, weight of splice bars and bolts, bolt dimensions, spike dimensions, and weight of rail in pounds per yard may be found in Parker (1970).

366. Thirty-six-inch track gauge is widely used when there is sufficient tunnel width, as this allows flexibility in using the same equipment on more than one job and raises resale value. Small equipment of narrow gauge may be used in small tunnels. On large tunnels 42-in. gauge may be used to provide a more stable track and a wider mucker cleanup width. On some tunnels equipped with specialized slusher trains or other specialized equipment, standard railroad gauge has been used. The weight of rail is determined by the maximum wheel load and the intended spacing. The larger the rail used in a tunnel, the more stable the track is and the fewer are the derailments.

367. The track bed in hard rock tunnels is generally strong enough after excavation. If the rock is fissured or uneven the rock might need grouting. If the tunnel floor is a soft material, the material will need to be compacted to support the maximum load anticipated.

368. Switching. Regardless of the mode of excavation, it is always important to be able to remove the muck as rapidly as possible. Muck disposal must be at the same rate as excavation to make the use of TBM's economical. Switching plays a very important part in an efficient rail haulage system. It is important to have mucking cars that are small enough so two cars can pass in the tunnel. Figures 58a, b, c, and d show four methods for switching cars.

These methods are discussed below. When the tunnel is wide enough for double tracks a California switch is used for car switching as shown in Figure 58a. A sliding floor is used with the California switch to advance the switching system with the tunnel face. If the tunnel is not wide enough to accommodate two cars side by side, the side transfer, cherry picker or grasshopper switching systems may be used.

369. The California switch is a portable combination of double siding and switch laid over the main track. This allows the main track to remain undisturbed while the portable track is moved into place to accommodate a car change. The loaded cars are pulled away from the mucker by one locomotive, and an empty car from the siding is placed behind the mucker by a second locomotive. When the tunnel has been advanced sufficiently the entire switch is pulled forward by the rail-mounted mucking machine and securely anchored in place until necessary to move it forward again. It can be moved forward 60-80 ft in about 30 min.

370. The sectional sliding floor version of the California switch shown in Figure 58b with a storage niche is installed at the face and is advanced by hydraulic cylinders as the tunnel is driven. It is wide enough to carry two parallel tracks and long enough so that cars can pass. Car transfer is handled by two locomotives which feed empties and pick up loads alternately. In addition to other advantages that reduce overall cycle time, the floor eliminates the need of short rail sections at the face to muck out long rounds.

371. In circular bores or headings where width does not permit double track, a cherry picker, such as shown in Figure 58c, can be used to raise a car vertically to allow a locomotive to pass, pull a loaded car away from the mucker, and feed in an empty. The picker consists of a framework supporting a hoist and sling, or hydraulic cylinder and rack arrangement. The cherry picker is frequently incorporated into a drill jumbo gantry that straddles the regular track and is mounted on temporary rails along the rib.

372. The side transfer may also be used when the tunnel is not wide enough for dual tracks. The side transfer car changer utilizes a moving platform to store an empty car on a transfer rail parallel to the main track. The changer is moved forward periodically to minimize locomotive travel and car change time. It is usually designed in sections which are lightweight to permit manual handling.

373. The grasshopper method of car changing shown in Figure 58d has lost favor in recent years because of its bulk and the necessity for extra rails. It requires the use of a steel frame about 150 ft long, traveling on separate rails set on each side of the main-line track. Hinged ramps at each end of the framework are operated by an air hoist. Tracks are laid up these ramps and over the deck of the framework. Six to eight empty cars are pulled up the rear ramp by a hoist and held on the top deck, and the rear ramp is then raised. After the mucker has loaded a car, the loaded car is pulled away from the mucker by a locomotive to a position clear of the front ramp of the grasshopper. The front ramp is lowered and an empty car is let down the ramp and coupled onto the mucker.

Rubber-Tired and Crawler-Mounted Mucking Equipment

374. Some of the primary advantages of using rubber-tired mucking equipment are its versatility (rubber-tired equipment can be used in tunnels with varying grades) and the fact that it eliminates the need for a separate loader in some cases, as well as eliminating the time-consuming chore of extending tracks for rail systems. Maintenance costs are low and reliability and availability are high. Another advantage is that rubber-tired trucks can haul beyond the portal to the disposal sites without rehandling. Rubber-tired muckers are used for loading or hauling, but crawler equipment is generally limited to loading. Modern equipment is powered by high efficiency diesel-powered engines, equipped with scrubbers to clean up exhaust emissions.

Crawler loaders

375. Crawlers are not used to haul muck because of their slow speed, but are used for loading muck onto train cars, conveyors, and dump trucks where traction is limited by wet or soft invert conditions. Three types of crawler-mounted muck loaders are rocker shovels, side loaders, and front-end loaders.

Rubber-tired loaders

376. Rubber-tired front-end loaders are used to load and haul muck in short tunnels (length less than 1500 ft) with grades less than 12 percent. These loaders can be used to muck the first 1500 ft of longer tunnels, if rehandling by trucks or load-haul-dumps (LHD's) are used at the transfer point.

Trucks

377. Trucks are probably the most versatile haulage units available for underground work. These units are fast (top speeds are near 30 mph), and they can be used for transporting men and materials, as well as muck.

378. Rubber-tired rear dump trucks with dual controls and gears for driving in reverse or forward may be used economically in tunnels having diameters between 12 and 30 ft. The length of haul should be less than three miles and grades should be less than 12 percent.

379. Rubber-tired rear dump tractor and trailer units require more passing room, more side clearance, and more loading room than rear dump trucks. They are used only in large tunnels (diameters greater than 30 ft). Maximum grade for these units is also about 12 percent. Maximum haul distances should be less than three miles, shafts should be spaced no further apart than this distance in long tunnels. The modern articulated tractor and trailer rigs are low profile and haul from 25 to 50 tons of muck. They can operate in more restricted spaces than the older models and have helped increase production in some mines and tunnels.

LHD units

380. A major advance in rubber-tired haulage occurred with the introduction of load haul dump units in the late 60's. LHD equipment has in most cases replaced the use of a separate mucker and haul trucks when the tunnel is so small that inline loading from the heading is required with rubber-tired equipment. Their loading efficiency is very good, and because of their crowding ability, the invert can be cleaned of nearly all muck.

381. Prior to this specialized equipment, the LHD concept was used in tunnel construction using standard cyclic loading machines. While adequate for short distances, their basic design was not recommended for haulage with loads for long distances.

382. The LHD, as its name implies, is a multiuse vehicle. LHD units, while basically for tramming, are well suited for cyclic loading of trucks. LHD bucket capacities range from 1 to 15 yd^3. The units can be used to transport men and materials to and from the face. LHD equipment cannot load standard off highway equipment so its high mucking capability is lost without special low profile trucks.

383. LHD's may be used alone and are usually less expensive for tunnels in the 7,000 ft or shorter range, where their slower speeds do not seriously

affect mucking rates. This distance can be extended to 10,000 ft by using another truck at a rehandling station (Scaravilli, 1977).

384. These units travel at speeds up to 12 to 15 mph or about half as fast as trucks. In long tunnels, it is normal to use LHD's and trucks together. Maximum economical distances are based on many factors, but the limiting cost factor is usually the extra capital cost of rubber-tired equipment versus a few more muck cars with rail.

385. For haul distances greater than about 10,000 ft, the ventilation requirements for the increased horesepower of these units becomes impractical in most cases.

386. In tunnels larger than 30 ft in diameter, direct heading loading of trucks is possible and the muck out rate will be better with LHD's than with rail systems. However, the cost of supplying enough trucks to keep the loader operating at maximum efficiency is high. With rail haulage, sufficient muck cars can be taken in to insure the full muck out of the round.

387. In large-diameter tunnels, the ventilation requirements, while increased, are more easily met because with the larger cross section, the ventilation line can be kept out of the travel way even if two lines are required.

388. Rehandling can extend the effective hauling distance up to 15,000 ft for tunnels in this size range.

389. Grades that exceed 3 percent for the loaded haul units favor the use of rubber-tired equipment.

390. Rubber-tired equipment can operate on up to 27 percent grades without cable assistance provided the road surface is concrete. With cable assistance, the LHD equipment can be used on even steeper grades.

391. Mobilization time and capital costs are lower for rubber-tired systems than for rail or any other system. Availability and reliability are good, and no time is lost in extending tracks or conveyors or pipes. Some of the problems experienced with rubber-tired systems include short tire life, oxygen starvation, and engine overheating. Improved tires and external tire protection has reduced the tire wear problem. Higher capacity cooling systems have helped reduce engine overheating. Oxygen starvation is caused by inadequate ventilation and high altitude operation and is a localized problem.

392. Rubber-tired units may be the only practical method of muck haulage in areas with grade and size changes. Manufacturers of some rubber-tired and crawler-mounted mucking equipment are listed in Appendix A.

Conveyor Systems

Tunneling applications

393. Conveyors can be designed for high-capacity, continuous muck haulage. Capital costs are high for conveyors. Maintenance and repair of conveyors is straightforward, but if one component of a conveyor system goes down, the entire job may have to be shut down while it is fixed. Belt breakage caused by abrasion is a common problem. Obviously, breakdown of one truck or one locomotive would be much less serious, and might not even slow the job noticeably. Installation time and costs are high for conveyors, and when they must be extended to keep pace with advance of the face, excavation usually has to be stopped. Maximum operating grade for conveyors is about 18-20 degrees, up or down. However, a cable suspension conveyor belt system has been used on inclines up to 45 degrees in Japan with good results.* This system, originally developed in Europe, has low power requirements and high reliability. When conveyors make up the entire muck handling system, separate means must be provided for transport of men and materials. For these reasons, conveyors are not often used in tunnel projects as a complete muck handling system. In most cases, rail or rubber-tired haulage proves more economical and reliable. However, conveyors are used extensively for muck loading. Practically all partial-face machines and all full-face TBM's have built-in conveyor systems to transport the muck from the face to the transfer point at the rear of the machine. The TBM conveyor is loaded by muck buckets mounted on the cutterhead of the TBM, which dump at the top of each revolution by gravity. The TBM conveyor dumps the muck onto a gantry conveyor which in turn loads the trucks or tracked cars that back under the conveyor. The loading conveyor is mounted on a rigid frame with wheels that are of wider gage than the train track and ride on separate tracks. The muck is fed from the conveyor belt to the first car behind the locomotive. As the car is filled, the train pulls forward until all the cars are loaded. A roadheader conveyor is fed by gathering arms mounted at the front of an invert shield (similar to a whisk broom and dust pan arrangement) which pull the muck onto the center conveyor. The conveyor transfers the muck to cars or trucks at the rear of the roadheader just as the TBM conveyor does. Figure 56a shows a loading conveyor and muck train.

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* Personal communication, Roger Johnson, CEMCO, August 1982.

394. Other than the use of conveyors for loading trains or trucks, conveyor belt trains are sometimes used in tunnels. The articulating cars making up the train have conveyor belts extending from car to car along the bottom of each car. As discussed previously, the loading procedure is to load the end car in a train with a mucker; the belt then moves the muck up the length of the train to the first car. When the first car is full, its conveyor is stopped and the second car is then loaded. The process is repeated until all cars are full. The conveyor belt is reversed to unload the train.

Mining applications

395. Conveyors are used extensively in mines as total systems. Mines are usually spread out in several directions and can use short feeder conveyors to feed the mainline conveyor from each face. If one feeder conveyor breaks down, the result is not too serious, but if the main-line conveyor breaks down, the job stops. In mining applications, the high capacity, uniform volume delivery, and relatively low power requirements are definite advantages of conveyors. Since electricity powers the conveyor, ventilation requirements are lower than for diesel trucks or locomotives. There are many types of conveyors, including chain and belt conveyors, fixed and extensible conveyors, bridge conveyors, and flexible conveyors. Most are so named because of the function they perform. Scaravilli (1977) discussed several applications of conveyors in United States mines. Bridge conveyors bridge the distance from the miner or tunnel machine to the feeder or main conveyor or to rail cars or trucks. The extensible belt conveyor (see Figure 59) is similar to other conveyors but has multiple pulleys mounted in the headpiece, around which the belt is woven. As the conveyor tail is extended the pulleys are drawn toward the middle, feeding out stored belt. These conveyors may be extended for 50 to 200 ft, depending on the amount of stored belt, before the unit must be stopped to add belt.

396. The tailpiece of an extensible belt is moveable and acts as a feeder for the belt proper. As the belt is advanced, quick-coupling idler stands are added. The idler stands are established by connecting bars locked into the adjacent stand.

397. A variation of the extensible belt has recently been introduced using modular units in which conveyor belt is not added or taken off. When retracted, the unit is 20 ft long and when extended, it is 150 ft long. The units are self tramming and are intended to be used in sets of two, three, or more.

398. An extension to the bridge conveyor concept was developed in the late fifties and early sixties utilizing a mobile bridge carrier and two bridge conveyors. The first conveyor bridges from the continuous miner boom to the inby end of the carrier and the second from the outby end of the carrier to the panel belt. Both the carrier and the panel belt are equipped with rails on which the bridges can slide. While the length of each unit can be varied, normally the bridges and the carrier are each 35 to 45 ft in length.

399. A recent approach to conveyor haulage is the serpentine belt system. This system consists of a pleated belt capable of turning corners and a wheeled, jointed conveyor structure. While the unit was exhibited several years ago it remains in the prototype stage, reportedly due to failure of the belt to remain on the idlers when turning corners in undulating floor conditions. The system was designed to be pulled by the continuous miner so that the function of the bridge carrier operation would be eliminated.

400. Armored conveyors are used exclusively on longwall mine faces and are an integral part of the mining system. While the primary function of the armored conveyor is to haul coal from the longwall face, in its present form it has other important functions. It must have sufficient structural strength to withstand the coal shearer riding on top of it, or in the case of a plow face, provide guidance for the plow and resist the heavy side pressures exerted upon it. The joints must provide flexibility during the snaking of the conveyor up against the face after the shearer or plow has cut the face. The conveyor must have a high capacity and must provide trouble-free operation over a long life span.

401. The armored conveyor can be driven by one, two, three, or four driving units on either or both sides. These drive units consist of an electric motor, fluid coupling and reduction gearing. The operating speeds of most chain conveyors are between 150 to 250 ft/min, matching the capacity of modern coal shearing machines. The armored conveyors in use are usually 30 in. wide and constructed of triangular steel plate sections each 5 ft in length and fabricated in one piece with 5 degree flexibility at each end. The armored conveyor is the most essential part of the longwall system and probably the weakest link (Scaravilli, 1977). Although longwall faces have been worked up to 900 ft in length, experience has shown that 600 ft is more reliable, primarily due to the limitations of chain pull and drive arrangements on current armored conveyors.

402. Belt conveyors may be characterized as high capacity, reliable coal haulers with high capital, and low operating costs. Intermediate belts servicing one section are generally 36 in. wide and belts hauling coal from multiple sections are 42 in. or 48 in. wide.

403. The belt conveyor system is composed of the belting, the structure, the drive and take-up mechanism, the loading and transfer points and the safety devices. Today, conveyor belts used in coal mines are made from polyester, nylon, and other synthetic materials. These materials provide strong flexible belts which are characterized by low stretch (less than 1-1/2 percent of the length). Steel wires are also used in belts where high tension applications, such as slope belts, are used to convey coal out of a mine.

404. Belt coverings are usually made from fire resistant materials, such as neoprene, in multi-ply belts. Cover thicknesses vary, but for coal mine applications top thicknesses of 1/8 in. and a bottom cover of 1/16 in. are common. Woven carcass belts of 5/16 in. total thickness are also used.

405. The strength of belts used today has been increased considerably and often 2 ply (or woven carcass polyvinyl chloride (PVC)) belt 36 in. wide are used to drive panels 3,000 ft long, while 3-ply 42-in.-wide belts are used for 4,000 to 5,000 ft belts. Most coal mines tend to standardize on motor drives. Seventy-five or 100-hp motors are used for panel applications, and 150- or 200-hp motors are used for main-line belts. Single drives are common in the former and tandem drives in the latter.

406. Belt structure used today is generally of the floor mounted wire rope frame type, which facilitates easier extension of the belt and easier belt alignment. The latest step has been to suspend the wire rope from the roof, thus permitting easier cleaning.

407. In recent years, belt capacities have been increased with the introduction of 35-degree and, in some cases, 45-degree idlers, together with the introduction of thinner, more flexible belts. Previously, when belts were less flexible, 20-degree idlers were required. A capacity increase of slightly more than 25 percent can be realized with a change from 20- to 35-degree idlers (Scaravilli, 1977), because the belt trough is deeper for the higher angle idlers.

408. Belt capacities are readily calculated from standard tables; however, for main belts serving multiple sections, the selection procedure is more complex. Belt speeds, method and rate of loading, willingness to delay

feeder belts, and placement of surge bunkers, all affect the selection of belt size.

409. In tunnels, the problem of belt sizing and speed is more straightforward; the maximum rate of muck production at the face is the design removal rate for the conveyor. Belt width and speed must be matched to handle this rate without overloading the system.

Pipeline Systems

410. Muck can be moved through pipelines horizontally, vertically, or on an incline using air or water as the transport medium.

411. Pipeline muck handling systems are termed "continuous" methods, as are conveyor systems. Pipeline systems have received much attention in the last decade (Faddick and Martin 1974, 1977a and b, 1978, Powell and Ruby 1981; and Duncan, Tierney, and Schneider 1970) in research papers and have seen limited use on actual tunneling jobs (Chrysanthou, 1970; Dahl and McCain, 1974; Nelson et al., 1975; Miller et al., 1977; and Lange, 1979). These systems offer high-capacity continuous service. Pneumatic or air pipeline systems have been devised to blow or suck the muck through pipes. Negative pressure is preferred because if a leak develops in a positive pressure system, dust escapes and makes working conditions poor. If toxic or explosive gases are present, leaks are not tolerable. Vacuum systems may be preferred for slurry pipelines also, because of the nuisance if leaks occur.

412. Figure 60 schematically shows a pipeline muck transport system. Pneumatic and hydraulic systems are described in the following paragraphs.

Pneumatic pipeline systems

413. Pneumatic conveying systems have proven to be economical for vertical muck transport in large mining operations. They are costly for horizontal hauls over 1,000 ft. The pipeline requires very little room, but the feeder and crusher may take up valuable space needed for another system to bring in materials and personnel. Experience shows that large-sized particles and "wet" material present problems. Dust control other than by water may be a necessary prerequisite. Pneumatic systems work best with dry granular material.

414. A pneumatic conveying system consists of (a) an air source, (b) an air lock feeder that places the material being conveyed into the pipeline, and

(c) a pipeline that transports the material to its point of discharge. Normally, a crusher or other muck preparation unit is also required. Sufficient air pressure is required to maintain particle transport velocities throughout the system. The air source is either a compressor or a blower. The latter is more common and is driven by a diesel or electric motor. A discharge silencer is used for noise control. The blower and motor may be located on the surface, at the base of a major shaft, or in a train in conjunction with the excavation machine and feeder.

415. The feeder is driven by a separate motor and can be skid mounted to follow a tunneling machine or be stationary. A common feeder consists of a rotary feed wheel with buckets that pass through a suitable air lock.

416. The pipeline is subject to high wear and is thus of two-layer construction having a mild steel outer shell and a highly abrasive resistant inner core. Pipes used in a pneumatic system must be carefully aligned, otherwise wear spots will develop downstream from the joint. Extension of the pipeline can be carried out by using telescopic pipes at the forward end.

417. In addition, a muck preparation unit is required to size the muck and pipe handling equipment must be provided for extending the system. The muck preparation unit consists of a screen, crusher, and conveyor that tracks behind the TBM and receives the muck from the bridge conveyor.

418. The pneumatic units trail the muck preparation unit, and consist of the storage bin, the loader, and the blower in positive pressure systems. Muck must be transferred at shafts or hoisted pneumatically.

419. The capacity of a pneumatic system, as reported by Faddick and Martin (1974), was limited to a maximum of about 3-in.-size rock through 1,000 ft of horizontal pipeline and 250 ft of vertical pipeline. Discussions with researchers indicate that these capacities can be increased, but not significantly in the context of very long tunnels. Booster blowers can be added at given intervals to increase transport distances attainable. Existing systems can economically handle muck transport (but not other materials and men) in 10- to 15-ft-diam tunnels provided that the muck is of suitable size and wetness (Crysanthou, 1970). A pneumatic system should not be used to handle wet, highly cohesive clay as elbow blockage and plugging of the hopper and feeder occur. In soft ground applications, fine particles may be highly abrasive.

420. Ventilation can be provided by the system if the blower is located in the tunnel.

421. The pneumatic system requires little labor and can be easily automated; however, it is extremely noisy in operation and this could be an environmental problem.

422. The installed power requirements at the face are high due to the inefficiency of blowers, but are of the same magnitude as conventional system power requirements for locomotives, ventilating fans, and car dumpers. One system reported in the literature (Matthews, 1982) required 800 hp to move 300 tons/hr over a horizontal distance of 1000 ft, or 14 hp/ton-mile/hr.

423. The principal advantages of a pneumatic system are that it can be used for either horizontal or vertical applications, and yet the pipes occupy a minimum of the tunnel cross sectional area. A further advantage is that, in case of a power failure, the material can be picked up from the bottom of the pipe by permitting the air to reach transport velocity before injecting more material when restarting the system. Offsetting these advantages, it is still necessary that a supplementary utilized transport system be provided for tunnel support materials and personnel. In addition to high horsepower requirements, it has the disadvantages of being unable to transport material larger than 3 in. or wet, sticky material. This latter restriction alone precludes its use on many projects.

424. A pneumatic pipeline system designed for possible use as a muck haulage system in a rapid transit tunnel excavated by a tunnel boring machine was recently tested by the Colorado School of Mines (Faddick and Martin, 1978).

425. The system comprises a muck preparation unit on skids including a crusher, screens, and conveyor belts; a skid-mounted blower and 500-hp motor; and a skid-mounted feeder and control console. The skids are connected to each other by tow bars, air pipe and muck pipe. The pipeline is about 500 ft long and is made of 10-in.-diam hardened steel pipe. Two telescoping pipes in series allow extensibility.

426. The first test phase used a pipeline configuration having a 26-degree slope for 325 ft, achieving a lift of about 150 ft. The second test phase used a rectangular pipeline configuration with additional elbows. The first test phase was designed to develop lift-capacity information while the second test phase was designed to develop information on wear, primarily on the elbows. For both pipeline configurations, the pneumatic transport system was tested for reliability, wear and maintenance requirements, capacity, noise

and dust levels, energy requirements, and operating costs. Moisture content effects and system extensibility were also studied. Rocks used were granite and hornblende with nominal top sizes of 3, 1.5, and 0.5 in. with loading capacities up to 100 tons/hr.

427. With a minimum number of elbows, the pneumatic pipeline system as tested was capable of transporting coarse muck at rates in excess of 100 tons/hr. Larger throughputs could have been transported if smaller safety factors were applied to overload protection devices on the equipment. There appear to be no technical constraints to building larger sizes of equipment to transport higher throughputs.

428. Wear was extensive on elbows, particularly flatback elbows in horizontal configurations. Round elbows have better wear life in horizontal configurations. However, wear life for any elbow geometry in pneumatic pipelines transporting coarse muck is not impressive judging by the results obtained in this study.

429. For the range of muck sizes studied (1/2 to 3 in.), moisture content was more important than particle size on the power requirements for pipeline transportation. There is a critical level of moisture below which the solids are lubricated and flow easily into the feeder, and above which, cohesive effects predominate causing the muck to be sticky. Power requirements for pipeline transportation of solids are reduced by higher moisture contents in larger particle sizes and increased by higher moisture contents in smaller particle sizes. A possible explanation is that moisture on large particles (which have small specific surface areas) is readily evaporated by the warm pipeline air giving a greater air density and viscosity which can support larger particles in suspension thereby reducing particle-wall friction and moisture on small particles (which have high specific surface areas) exerts high surface tension forces to hold finer particles together resulting in higher pressure drops to transport these agglomerates.

Hydraulic pipeline system

430. Hydraulic pipeline systems have been described by Faddick and Martin (1974, 1977a and b, and 1978); Nelson et al. (1975), and Miller et al. (1977).

431. A hydraulic system is relatively simple in operating principle. Water is the transport medium and can be recirculated from the system terminals if a good source is not available. It is mixed with the excavated

material in a mixing chamber or tank, producing a slurry which is pumped into a pipeline that carries the slurried mixture to its destination. Here, the solids are separated from the liquid through a dewatering process, or transported elsewhere in the slurried form for further processing. Sufficient system pressure is required to maintain particle transport velocities, and the use of crushing equipment ahead of the mixing operation is usually required to obtain the correct particle sizes.

432. Design criteria for slurry pipelines hinge around particle size and distribution. A small muck size means lower energy requirements for pipelining, lower water requirements, lower operating velocities and lower pump/pipe wear. The disadvantages are the cost and physical size of crushing and dewatering equipment. However, if the particle size is too small, the viscosity of the slurry increases substantially leading to an increase in the energy requirements for pipeline transportation and may cause blockage of the pipe, especially at elbows.

433. On the other hand, a coarser muck size means higher energy requirements for pipelining, higher water requirements, higher operating velocities, and hence, higher pump/pipe wear. The advantages are reduced crushing and dewatering equipment sizes and costs. Minimum crushing and dewatering costs are to be preferred for any slurry pipeline transportation system.

434. Considerable work has been done on fine slurry systems. The role of rheology is fairly well established (Faddick and Marcin, 1974). Rheology is the study of deformation by shearing of fluidlike materials. The accumulation of fines in a slurry constitutes the development of a "heavy medium" capable of supporting coarser particles in suspension and thereby reducing the overall energy requirements for pipeline transportation. The effects of fines on the energy requirements for pumping slurries can be ascertained by rheological tests.

435. Normally there is insufficient water in the tunnel for the system and two pipelines are needed, one for slurry and one for recirculated water. Low head slurry pumps are used to move the muck and water. These pumps generally have high maintenance costs.

436. System extension is difficult if continuous flow is required. One method is to utilize duplicate sets of slurry mixing equipment and manifolded charging pumps complete with valving and bypasses. The valves and bypasses are left in place as the advance progresses, with the mixing and pumping

equipment "leapfrogging" for each increment of pipe advance. This requires a high inventory of valves and uses up valuable working space. The necessity of a supplementary material and personnel transportation, and the restriction of small particle sizes tend to make this system inappropriate in most cases.

437. There are cases where these systems have been used successfully. Tunnels in Japan and the United States (North Point section of sewer tunnel, San Francisco, Calif.) have been driven using the slurry pipeline muck removal system in conjunction with the earth-pressure balanced shield developed by the Japanese. The San Francisco tunnel was driven by Ohbayashi-Gumi Ltd in 1981. This tunnel was 12 ft in diameter and 3100 ft long (Thon, 1982), and was driven through soft clay with about 30 ft of overburden.

438. Nelson et al. (1975) and Miller et al. (1977) reported the use of hydraulic pipeline muck handling in conjunction with hydraulic erosion tunneling in the soft St. Peter sandstone of the Minneapolis-St. Paul, Minn., area. This tunneling method was developed over 40 years ago and consists of cutting and disintegrating the sandstone with low-pressure water jets and pumping the resulting slurry out of the tunnel. The authors report that the system has been so successful that essentially the same technology is still used to produce some of the lowest cost urban tunnels in the nation ($500 to $600 per linear foot, 1977 dollars), based on 85-ft^2 cross section, and including excavation, primary ground support, and 1-ft-thick final lining. Two important considerations that make this method viable in this area are an abundant source of water (the Mississippi River) and very weak rock (unconfined compressive strengths approximately 500 psi).

439. In summary, pneumatic or hydraulic pipeline systems appear to be technically feasible with available commercial equipment. Pipeline haulage systems are capable of transporting large quantities on a continuous basis. Pipeline transportation costs decrease on a unit basis as the haulage distance and throughput increase. Slurry pumping and separation (dewatering) comprise about half of the total transportation cost. Because pipeline systems have seldom been used in tunnel construction, it is quite possible that these costs could be reduced significantly as experience is gained. This would appear to be particularly true for the separation systems which have had very little exposure to tunnel muck and the design constraints of this application.

440. A pneumatic pipeline unit can provide satisfactory system extensibility in conjunction with a slurry pipeline. Only an extensible conveyor

system appears at this time to be an acceptable alternate. The price of extensibility as achieved by a pneumatic pipeline represents about 20 percent of the total cost of the pipeline transportation concept.

441. Muck transport with a pneumatic pipeline system with telescoping pipe has merit particularly for short distances, that is, short tunnels or long tunnels with intermediate shafts.

442. The unit cost of transporting tunnel muck varies widely with muck size, tunnel length and diameter. While costs appear high, information on comparable current costs for other tunnel haulage systems is sparse because of different accounting methods, different excavation methods and tunnel geometry. Until such comparisons are made on a standard basis, it is difficult to assess the cost-competitiveness of pipeline transportation systems for tunnel excavation.

Muck Loading in Shafts

Conventionally sunk vertical and inclined shafts

443. Mechanical mucking equipment is commonly hydraulic or air powered. Generally, the machines being used are either a form of clamshell suspended from the working platform or set into the wall, or are crawler-track, bucket-loader machines which move on the muck pile itself. The Eimco 630 is a small, air-operated, crawler-track bucket loader and is the most widely used. The machine is approximately 5 ft, 8 in. wide; 4 ft, 11 in. high; and 9 ft, 5 in. long. The length and height may vary with different bucket sizes and bucket positions. The complete machine weighs 10,000 lb. Several bucket sizes are available from 5-1/2 to 9 ft^3 (Dames and Moore, 1977). While its production rate is slightly lower than that of grab devices, it has the advantage of being able to crowd into the muck pile for efficient loading and is capable of cleaning even minor amounts of muck at the end of a loading cycle. It is a very effective unit when used in shafts 18 ft in diameter or greater. Where water and soft-ground conditions are encountered, however, these units frequently are replaced by other mucking methods because of problems with the mechanical tracks and water entering the motors (Cummins, 1973). Clamshells may be used from a surface-mounted crane or adapted for use at the bottom of the shaft. The clamshell is operated from the shaft bottom by a miner using a

button box control or swung by two other miners using tag lines. Backhoes, in several forms, have been used on United States shaft projects with limited success, their main disadvantages being a relatively low production rate. The machines are either hung from the surface or a work deck, or are mounted on the rib. The Cryderman mucker is an air-operated machine with a positive, opening-and-closing, clamshell-type bucket. It may be either hung vertically in a shaft or mounted on small rail cars in slopes. This machine has the advantage of positive closing, allowing it to dig into the muck for better loading. It can also be used near the end of the mucking cycle when little material remains in the shaft. The cactus grab or orange peel is a multi-leaved clamshell-type machine suspended from either a centrally pivoted boom hung below the work stage or on hydraulic booms mounted on inserts placed into the shaft lining. The operator controls the machine from a cage suspended from the work stage or from a remote control box at the shaft bottom. The cactus grab works well in circular or elliptical shafts. It has a high production rate and has been used with much success in South Africa. The Riddell mucker is similar to a cactus grab and consists of a small clamshell bucket hung from a bridge below the work stage. It is most effective in small, timbered shafts or in locations where water is encountered that presents problems for other types of mucking equipment (Cummins, 1973).

444. A Cryderman mucker is normally used in inclined shafts because its clamshell bucket is mounted on a rigid boom that can be hydraulically supported and maneuvered. The bucket must be supported to keep it off the bottom of the shaft while the face is being mucked.

Shafts sunk by the impactor method

445. Mucking is accomplished with the backhoe on the impactor unit, which transfers the rock into conventional muck buckets for hoisting. Either a single or double drum hoist can be used, but it must be of sufficient capacity to minimize muck hoisting cycle time. The cycle of muck haulage is continuous during rock breaking and is halted only during shaft lining. It is possible to continue mucking during lining (since breaking is possible during the lining phase), although this approach would require that the concrete be delivered down the shaft by slick line instead of the muck buckets.

Large-diameter drilled shafts

446. Cuttings are removed from large-diameter drilled shafts by reverse air or water (or mud) circulation. Air compressors or water pumps are required and a tailings pond is required when water or mud is used to reclaim the fluid.

Conventionally raised and raise-bored shafts and reamed shafts

447. Muck loading is not required in conventionally raised or raise-bored or reamed shafts. The muck falls to the bottom of the shaft by gravity. Diversion chutes may be used to prevent damage to equipment or injuries to miners below the shaft. Removal of cuttings from the pilot hole of raise bored and reamed shafts is accomplished by direct or reverse circulation of drilling fluid (air, water, or mud).

448. The V-Mole works similar to a reamer but is a rodless machine. The cuttings from the pilot hole are removed as stated above. The muck from subsequent enlargements to the desired diameter fall to the bottom of the shaft through the central hole.

Blind-bored shafts

449. Removal of cuttings from blind-bored shafts has been the main obstacle to success with this shaft sinking method. The Robbins machine used flight conveyors that scraped the muck from the face. These conveyors wore excessively and allowed muck to build up at the face, slowing progress. The skip-hoisting system also experienced problems with leakage of wet muck and sequencing. A pneumatic-hoisting system has been tested for use with the blind-shaft borer and showed much improvement over the flight conveyor system. However, it has not been installed and tested with the borer.

450. Recently the Wirth V-Mole machine was redesigned and built to blind bore 5.8-m shafts. A hydraulic pickup and hoisting system was successfully used with this machine (Tunnels and Tunneling, 1983). Further details were unavailable at this writing.

Muck Hoisting in Shafts

451. The hoisting system is perhaps the most critical component in conventional shaft excavation. In vertical shafts or steeply inclined slopes, the hoisting system is the sole means of access. Men and materials are raised and lowered by means of the hoist, and the broken rock is hoisted to the surface for disposal. Hoists are mechanically-driven drums which raise or lower a load by winding in or playing out a length of wire rope. There are two basic types of hoists in use today--the friction, or koepe, hoist and the drum hoist. In addition the main hoist and work deck hoists, small air winches

(tuggers) are used for a variety of tasks, such as in an emergency escape system or to lower concrete slicklines, remix chambers, and handle concrete forms and steel ventilation tubing. Crossheads are commonly used in conjunction with rope guides to prevent buckets from swinging or spinning while being hoisted. The crossheads are steel structures that ride on platform suspension ropes and are designed to lock onto the main hoist rope at the bucket attachment to provide stability for the bucket. The hoisting system in inclined shafts is different from that used in vertical shafts. The skips ride on rails installed in the shaft and are raised and lowered with a winch and cable system.

452. Muck hoisting can limit the progress of mechanical shaft excavation systems, and even in conventional shaft sinking, muck hoisting if a time-consuming chore. Actual hoisting times are fairly fast, but simply picking up the cuttings from the face takes a large amount of time. A successful vacuum pickup system has been tested for the blind shaft borer as has a companion pneumatic hoist. These systems were discussed in the preceding muck handling section. Reverse circulation systems for removal of cuttings are inherent to the large-diameter drill design, and moving the particles across the face to the pickup point more rapidly has been attempted for years. Face clearing is the major constraint to higher drilling rates and shaft boring rates.

453. During the shaft collaring operation, common to all shaft sinking methods, a mobile crane is used to hoist the muck and lower supplies to the crew. Special modifications, such as overspeed and overwind switches, must be made to the equipment to make it conform to the appropriate MSHA regulations. These cranes can be used from 50 to 200 ft from the surface before MSHA regulations require rope or metal guides for the bucket. Use of a crane to greater depths aids in the installation of the sinking headframe and work deck.

454. Sinking hoists are usually old production hoists, but some are specially designed. Using old production hoists significantly increases the time needed to mobilize the shaft sinking equipment. Older hoists require special foundations and alignment methods because they were generally designed for permanent installations. The broken rock is hoisted to the surface in open muck buckets that usually consist of two round or square containers of roughly 3- to 5-ton capacity. In some deep shafts it has been necessary to use three buckets to maintain the desired sinking rates.

455. Pneumatic hoisting systems were developed a number of years ago and are currently being successfully used for hoisting raw coal by the National Coal Board in the United Kingdom (Peters, 1977; Ball and Tweedy, 1975; and Powell and Whitfield, 1978). Air forced through the pipes at high speeds but low pressures (20 psi) conveys the particles at speeds exceeding 120 mph. Over-4 in-feeds and minus-3-in. feeds have been hoisted to the surface at about 200 mph. The problem of developing sufficient acceleration of the muck in the short horizontal distance available in a shaft was recently claimed to be solved through extensive laboratory testing and full-scale tests in an actual mine shaft ("Pneumatic Hoisting System for the Blind Shaft Borer," 1978). Pneumatic systems can accommodate particles nearly the size of the pipe diameter, but the particles should be limited to half the pipe diameter to avoid blockage. Therefore, a grizzly or other particle classifier is needed. Full-scale tests show that the pneumatic hoist could easily handle the output of a blind shaft borer (Radmark Engineering, Inc., 1978). Also, pneumatic systems have been used in hoisting raise-borer cuttings up through a nearby shaft rather than conveying them by the mine transportation system. An advantage of the pneumatic hoist system is its ability to transport large amounts of water should the need arise.

Transport of Men and Materials

456. Transportation of men and materials is normally accomplished by the muck handling equipment except in the case of the conveyor and pipeline systems. Trains carry muck, men, and equipment to and from the tunnel. After the cars are emptied during a mucking cycle the cars may then be loaded with supplies needed in the tunnel. Rubber-tired mucking equipment double as personnel and equipment transporters in some tunnels. Companies such as Eimco (Mining Machinery International) and Geterman Corporation make special equipment for servicing other equipment, carrying personnel, lubricating equipment, carrying and handling explosives, and hauling supports. This special equipment must be used for carrying personnel and equipment where conveyor or pipelines are used to transport the muck.

Summary and Comparison of Muck Handling Methods

457. Muck handling may be accomplished by rail-mounted systems, rubber-tired, or crawler-mounted equipment, conveyors, or pipelines.

458. Rail systems are used extensively in mines and tunnels. High capacity, high reliability, and low energy costs per unit volume moved are well-known advantages of muck trains. High capital and installation costs offset these advantages in short tunnels. Trains can be electric, diesel, or supplemental battery-trolley powered. Rail haulage is restricted to grades of 0 to 3 percent, unless a cable assisted system is used. A separate loader is required and may be a conveyor or rail-mounted mucker or rubber-tired or crawler loader. Some rail muck cars are self-dumping; others require assistance of a rotary dumper.

459. Rubber-tired muck handling systems may consist of rubber-tired loaders and trucks, or LHD units, or combinations of LHD's and trucks.

460. Rubber-tired systems are versatile and can be used for hauling muck and transporting men and materials on varying grades up to 27 percent or so if a concrete roadbed is provided. Maximum grades of about 12 percent may be negotiated if the roadbed is not concrete. Extensibility of truck systems is inherent, no extensions to rail or utilities is required. Because trucks are primarily diesel powered, high ventilation requirements limit their use in long tunnels, especially small-diameter tunnels. In small-diameter tunnels there is insufficient clearance for the ventilation lines. In tunnels smaller than below 12 ft diam, there is not enough clearance to load trucks. In such cases LHD's may be used effectively for haul distances up to 7000 ft or so. This distance can be extended if rehandling stations are used. LHD's are slower than trucks (maximum operating speeds are about 30 mph for trucks and about 12 mph for LHD's) and capacities are lower, ranging from about 1 to 15 cy for LHD's. Truck capacities range from 25 to 50 cy. These capacities are considerably less than rail systems, but much shorter travel times for trucks offset this disadvantage.

461. Crawler loaders can be used in wet headings where the invert is in poor condition. Crawler equipment is too slow for haulage.

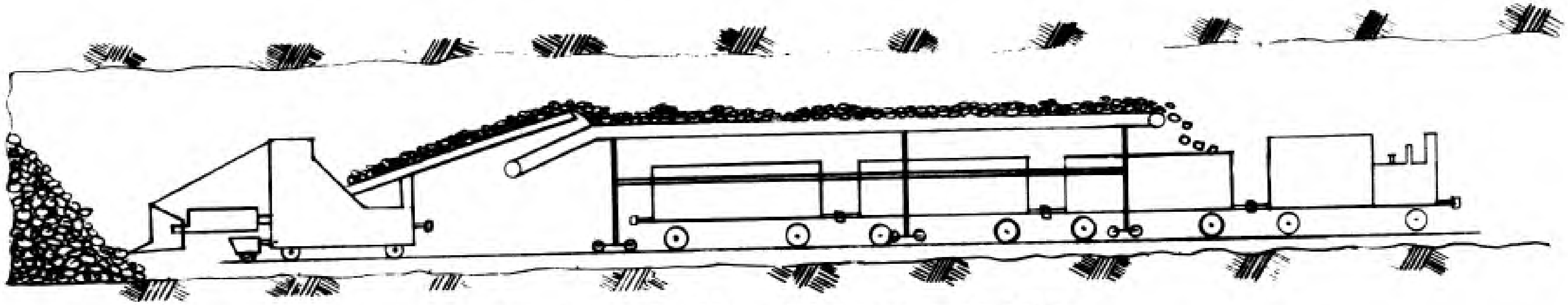
462. Conveyors are used extensively in mines as total muck handling systems, and are highly regarded for their high reliability andlow operating costs. In tunnels, conveyors are used primarily for muck loading only.

Conveyor systems have high capacity and are simple to repair, but have high capital and installation costs, a disadvantage for tunneling. In addition, extension of the system to keep pace with excavation usually causes some delays; extensible belt conveyors can be used to minimize disruptions caused by extension. Conveyors can be used in virtually any size tunnel; maximum grade is limited to about 20 degrees or 45 percent, up or down. Maximum muck size should be less than about 12 in. Power requirements are low; conveyors are efficient materials handling systems. But if one component breaks down, the entire system must be stopped until repaired. Separate means must be provided for transport of men and materials. Wet, sticky materials cause problems with conveyors. Dust is a problem in dry headings, but dust is a problem with any muck handling system. Conveyors are powered by electric motors so ventilation is not a problem, except for dust removal.

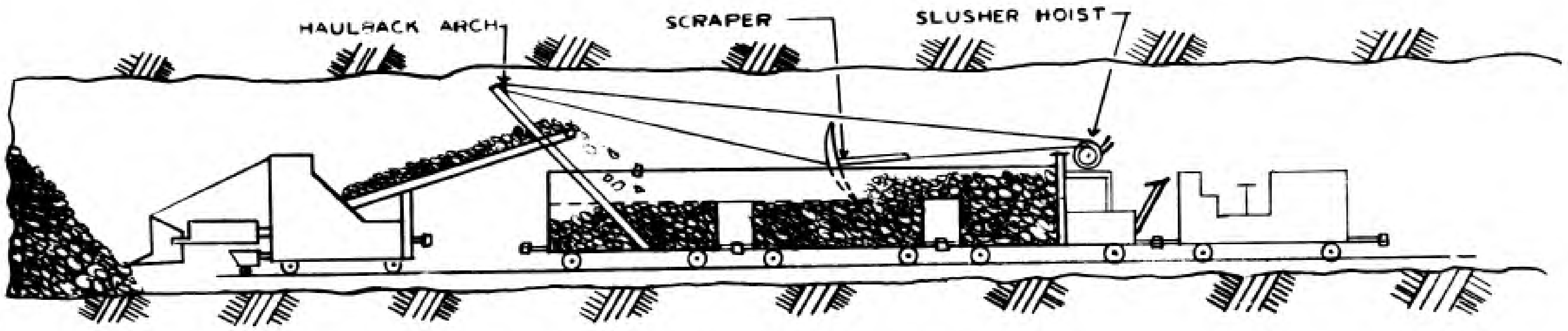
463. Pipeline muck handling systems have seen limited use in tunnels and shafts. The muck transport medium may be water or air. The systems generally consist of a muck crusher, a feed bin and feeder, pipe, elbows, and pipe supports, and blowers or compressors for air systems or pumps for slurry systems. Muck size and transport distances are very important considerations. Moisture content is critical for air systems. If the material is very wet, power requirements are higher; sticky fines may plug the pipe. Repairs require that the system be shut down. With slurry systems, the pipe systems must be emptied before repairs can be made and before the system can be extended. A water supply and settling basins must be provided for slurry systems. Pipeline slurry systems have been used to advantage with hydraulic erosion tunneling in weakly cemented St. Peter sandstone in the Minneapolis-St. Paul area. As with conveyors, of course, separate means must be provided for transport of men and materials.

464. Muck loading in shafts may be accomplished with clamshell diggers or track-mounted equipment. Shafts sunk by the impactor method rely on the backhoe attached to the galloway frame. Muck loading is not required for large diameter drilling or for conventionally raised or raise bored or reamed shafts. Muck loading problems have been the main obstacle to successful use of the blind shaft borer. Bucket elevators were tried and performed poorly. A pneumatic pipeline system has been tested and shows promise. A hydraulic pickup and hoisting system was used with the Wirth blind-shaft borer.

465. Muck hoisting in shafts is often done with a headframe, winch, cable, and skip system. Pneumatic or hydraulic pipeline systems have seen limited use. Bucket elevators have also been used. Reverse circulation of drilling fluid is used to remove cuttings from large-diameter drilled shafts. Direct or reverse circulation is used to remove cuttings from the pilot holes for reamed shafts.

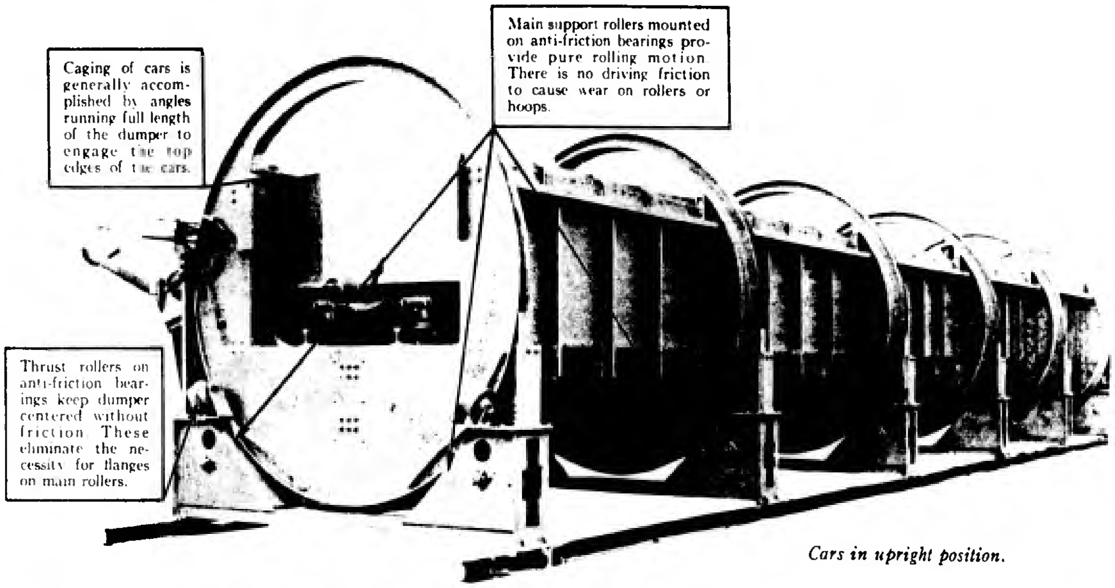


a. Train loading with a conveyor belt



b. Train loading with a slusher scraper

Figure 56. Train loading

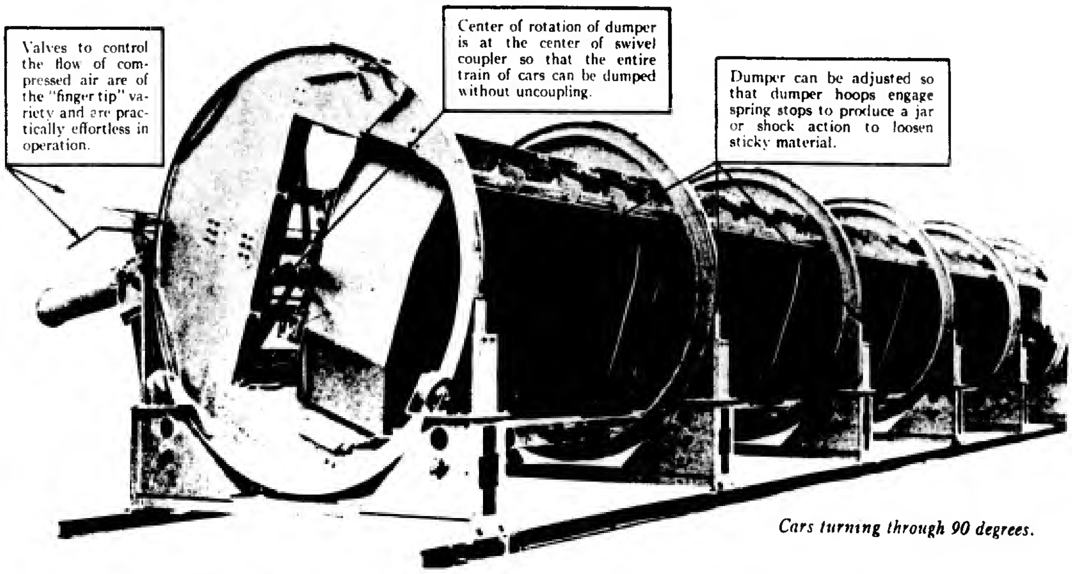


Caging of cars is generally accomplished by angles running full length of the dumper to engage the top edges of the cars.

Main support rollers mounted on anti-friction bearings provide pure rolling motion. There is no driving friction to cause wear on rollers or hoops.

Thrust rollers on anti-friction bearings keep dumper centered without friction. These eliminate the necessity for flanges on main rollers.

Cars in upright position.

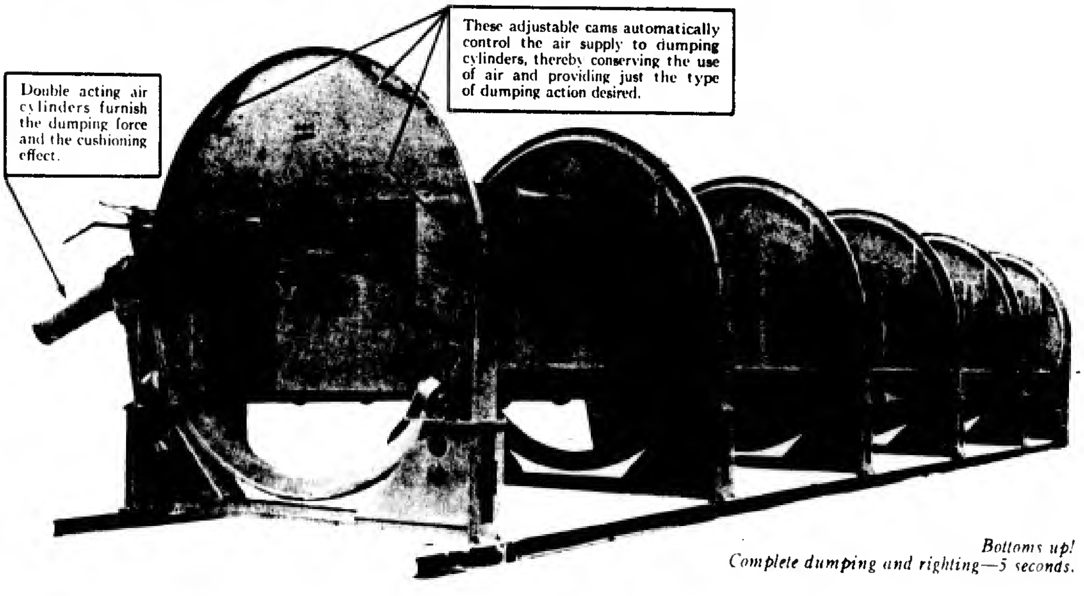


Valves to control the flow of compressed air are of the "finger tip" variety and are practically effortless in operation.

Center of rotation of dumper is at the center of swivel coupler so that the entire train of cars can be dumped without uncoupling.

Dumper can be adjusted so that dumper hoops engage spring stops to produce a jar or shock action to loosen sticky material.

Cars turning through 90 degrees.

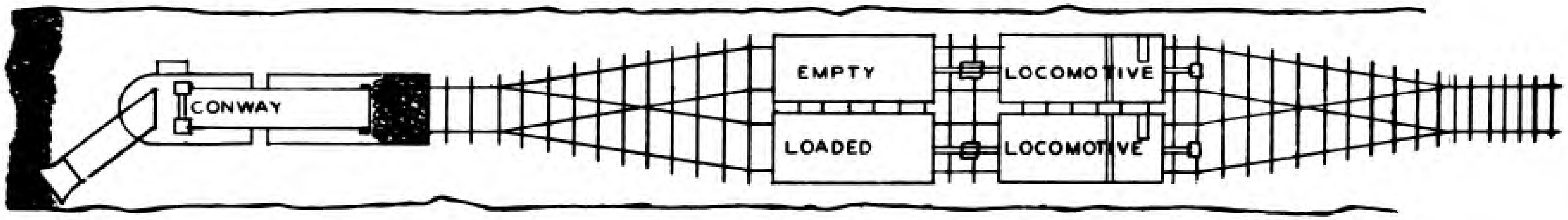


Double acting air cylinders furnish the dumping force and the cushioning effect.

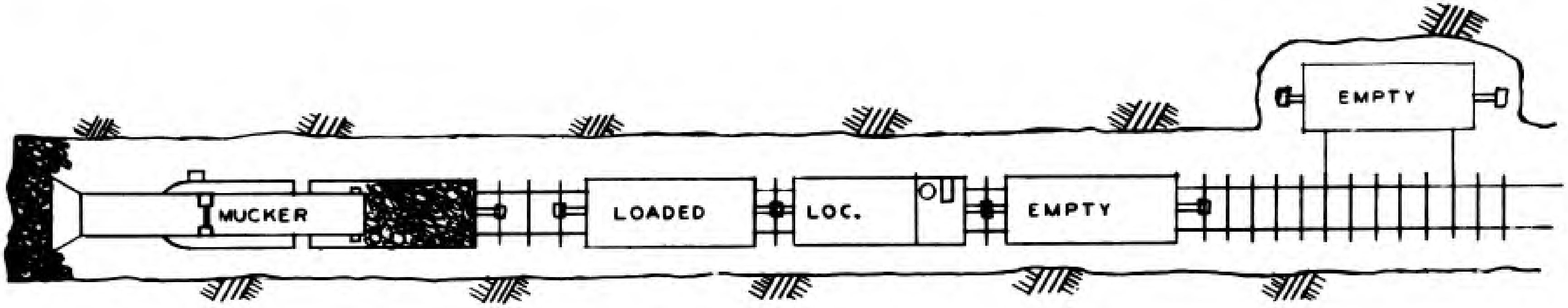
These adjustable cams automatically control the air supply to dumping cylinders, thereby conserving the use of air and providing just the type of dumping action desired.

Bottoms up!
Complete dumping and righting—5 seconds.

Figure 57. Five-car rotary dumper

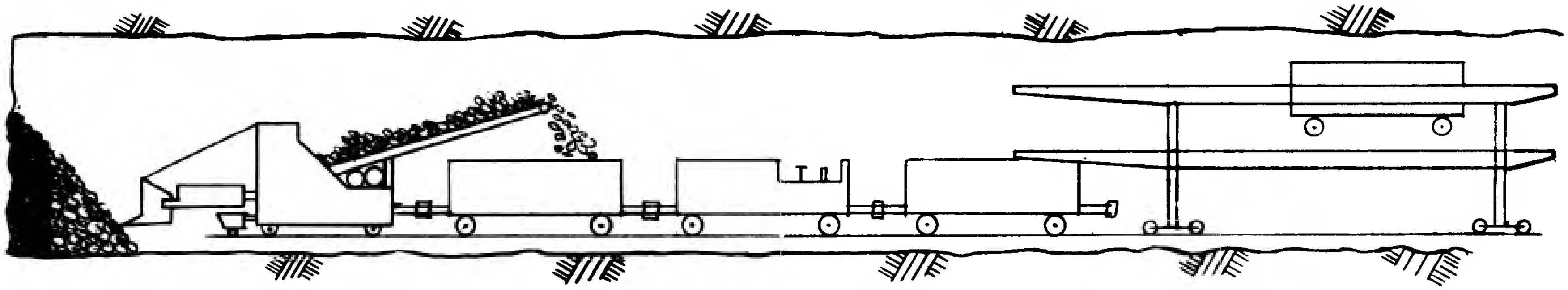


a. Car changing with a California switch

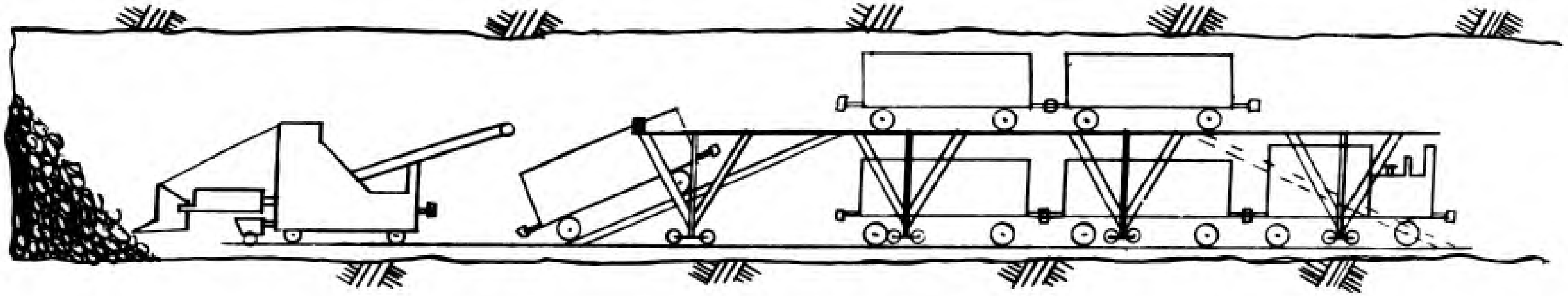


b. Changing cars using a car passer with a storage niche

Figure 58. Changing cars (Continued)

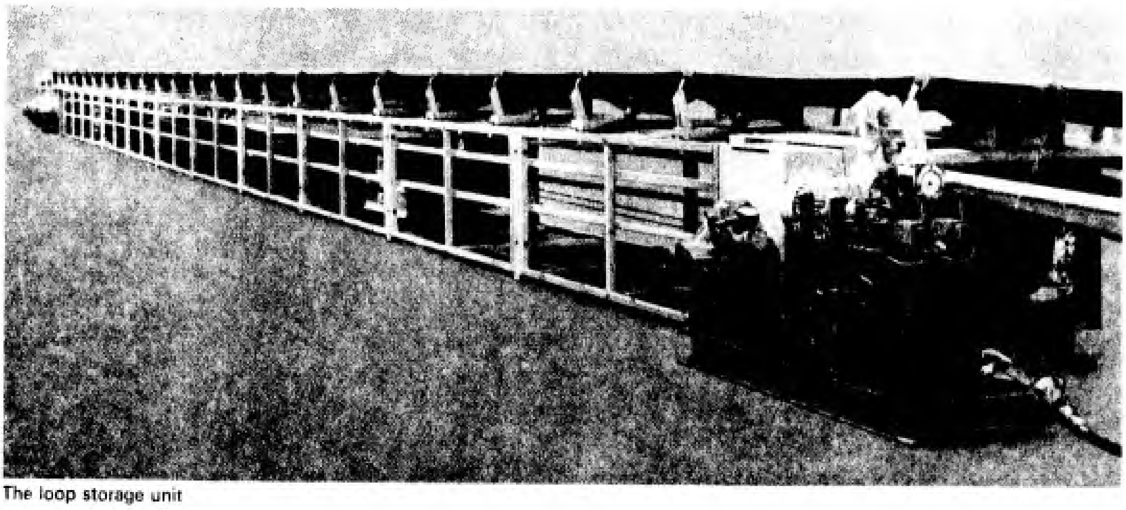


c. Changing cars using a cherry picker

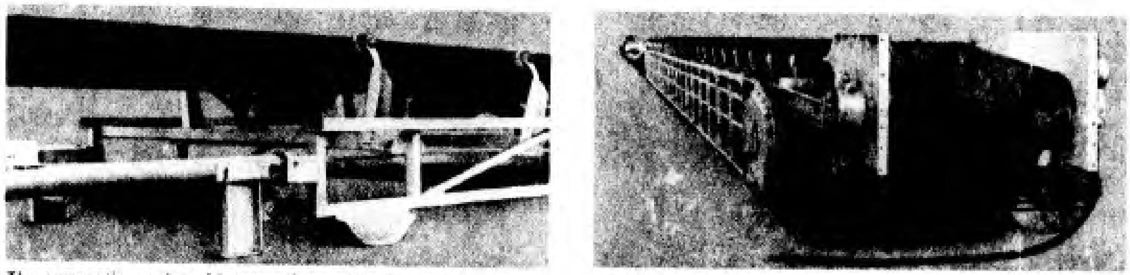


d. Car changing using a grasshopper

Figure 58. (Concluded)

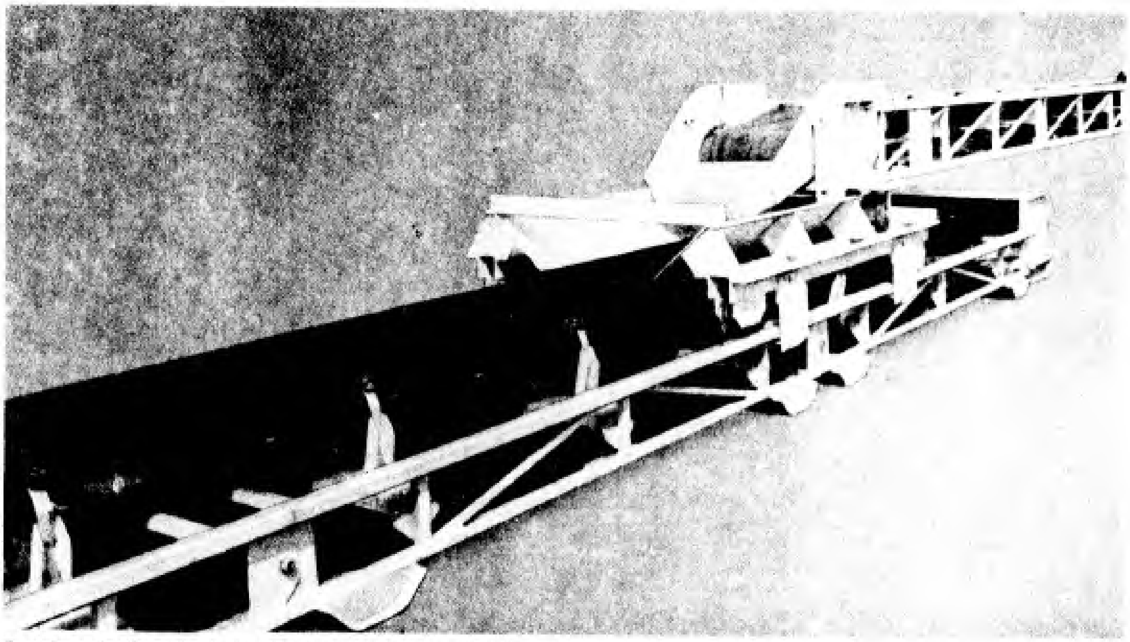


The loop storage unit



The connecting point of intermediate and tail end units

This side of the conveyor is almost completely flush



Transfer point from the bridge conveyor to the tail end unit

Figure 59. Extensible belt conveyor

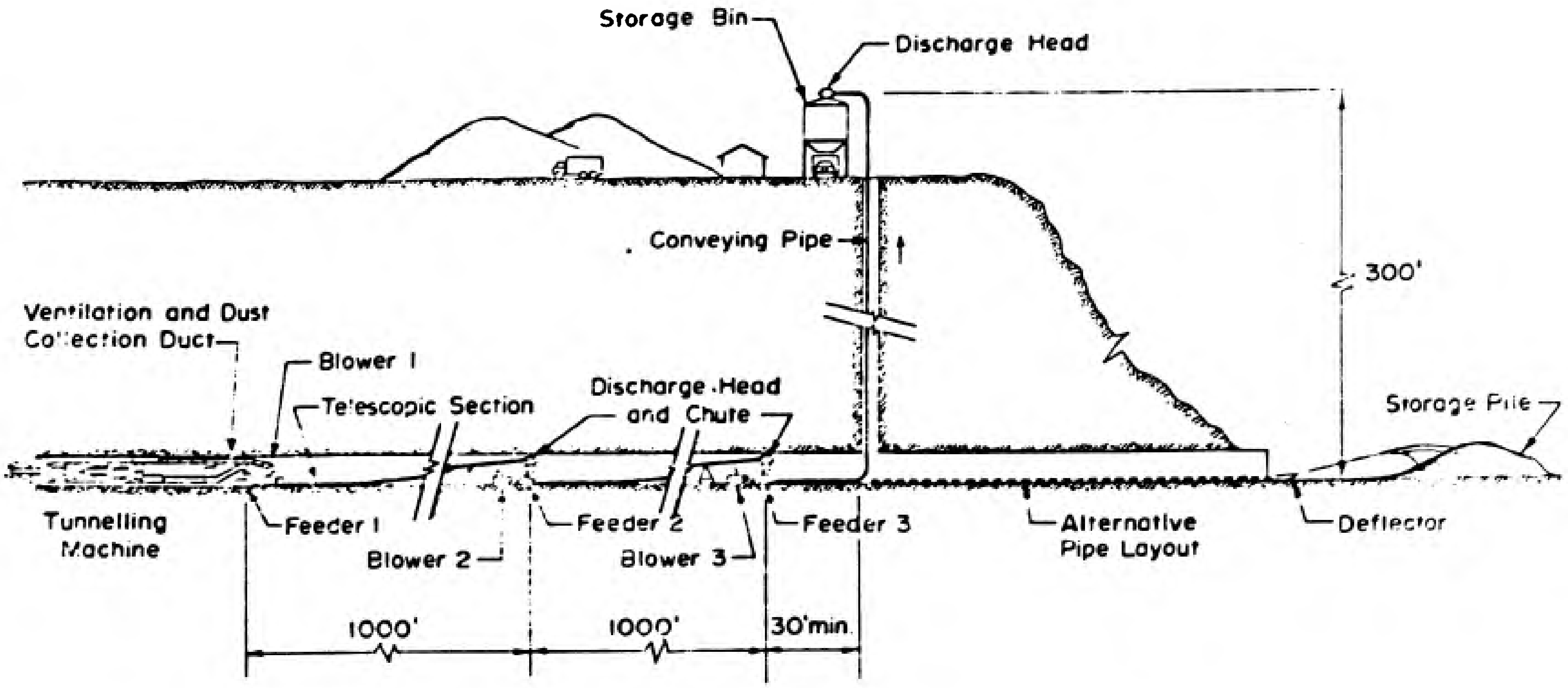


Figure 60. Typical layout for pipeline muck handling system

PART V: SUPPORT AND LINING

466. The choice of support or reinforcement system is a major factor in any tunnel or shaft project. The support or reinforcement system not only ensures the stability of the opening, the integrity of the overlying surface structures, and the safe use of the finished tunnel, but can significantly affect the cost and rate of advance of the tunneling or shaft sinking operation. Heavy supports and final lining can be one of the largest single cost items of the project and can amount to as much as 40 percent of the total cost.

Tunnel Support and Lining

Versatile and adaptable support concepts

467. Two basic philosophies exist for design of tunnel support. The versatile support concept implies that a single support system capable of supporting the excavation in the worst rock conditions expected will be used throughout the tunnel length. Support design will be conservative in zones of better rock and adequate in the worst conditions. Material costs will be higher than necessary in the good rock. However, advance rates will be predictable and methodical as the crew can develop proficiency using a single support system. In addition, only one type of support has to be stockpiled at the site, which saves space.

468. The adaptable support concept implies that ground support will be designed to different load capacities, corresponding to identified zones of variable rock conditions. Support design is less conservative and cost of the support itself will be less expensive. However, several types of support may have to be stockpiled to meet quickly changing conditions. Each time the support system is changed, advance rates decrease until the crew becomes proficient in its installation.

469. Many improvements have been made in recent years in reinforcements, supports, and linings. These include thin layers of shotcrete applied directly behind the tunnel face in practically all types and quality of rock; expanded precast concrete segmental liners in firm soils and rock; preformed interlocking steel sheet liners; development of rock bolting and shotcrete to provide minimum support to the rock mass; and more recently, a tunneling

machine has been tested which extrudes a continuous shell of steel fiber reinforced concrete that acts as primary support and final lining (Martin and Braun, 1982).

470. Primary reinforcement or support is that required to maintain the structural integrity of the tunnel during construction. This may be for only several hours or could be for several months. The final support or lining is considered with due regard to the use and life expected of the tunnel. For instance, a subaqueous road tunnel under a river may have a design life of 50 years and also allow for a ship sinking and coming to rest over the tunnel. In contrast, a mine roadway having a limited life of only a few months would have the minimum support necessary to insure stability and meet applicable mine safety regulations.

471. The design of reinforcements, supports, and linings is still very much a balance between art and science. In soft ground tunneling, designs based on the deformation of an elastic medium are used. For rock tunnels, designs based on rock quality properties are widely used. These design systems rely on geotechnical assessment and analysis of empirical data from case histories, based on work carried out by Wickham, Tiedemann, and Skinner (1974), Bieniawski (1974), Barton, Lien, and Lunde (1974), Deere et al. (1969), Terzaghi (Proctor and White, 1946a), and others. Craig and Muir Wood (1978) have produced a comprehensive review of tunnel lining practice, and Bieniawski (1979) reviewed empirical methods of support design.

Soft ground tunnel support and lining methods

472. Past practice has been to immediately erect primary support and place secondary or permanent lining at a later date. When TBM's are used, it is now common practice to use only one lining, which is erected in the tail of the shield immediately after excavation and which serves as both primary support and final lining.

473. Primary support for soft ground may be divided into the following types: steel ribs with timber or concrete lagging, shotcrete, segmented liners of concrete, steel or cast iron, or cast-in-place concrete. The lining is usually designed to carry the full ground load.

474. Steel ribs and lagging. Steel ribs consist of relatively light sections which are preformed to the final shape required for the tunnel. In most cases they can be conveniently transported to the face in empty muck

units and may be installed by hand or by means of an erector arm mounted in the tail shield of the TBM. Joining plates with elongated holes can be used to secure the expanded steel ribs against the ground, thereby preventing ground movement of any magnitude. The lagging placed between the flanges of the arches may consist of timber, precast concrete, or pressed steel plate units.

475. Spacing of the steel ribs varies, depending on ground conditions and contract specifications. The ribs may be placed at 3- to 4-ft intervals in TBM driven soft ground tunnels, as this is the normal cyclic advance of a TBM. Steel ribs and lagging cannot be made watertight so a secondary lining of concrete is usually necessary to minimize leakage if required.

476. Liner plates. Liner plates consist of prefabricated pressed steel segments which are rolled to shape specifications by the factory and reinforced by flanges along the four edges or by a series of punched flanged holes across the plate. The gauge bolt spacing and other dimensions depend upon the tunnel diameter and loading; the segments are typically 16 to 20 in. wide and weigh between 25 and 80 lb. In a majority of cases they can be placed by hand or with simple erection equipment. Solid plates can be installed with gaskets in ground conditions where water is a problem. However, in soft-ground conditions all liner plate systems require a secondary concrete lining for corrosion protection. The principal advantage of the liner plate is its standardized design.

477. Shotcrete. Shotcrete is a sprayed concrete lining applied to tunnel walls immediately after excavation. There are many examples of the use of shotcrete in soft-ground tunnels, although it is primarily used in rock construction. Shotcrete thickness varies, depending on factors such as ground conditions and contract specifications, but shotcrete thickness is usually 4 to 6 in. In soft-ground or poor rock conditions shotcrete is applied immediately after excavation, before deformation and loosening of the ground occurs.

478. Shotcrete can be applied over steel ribs, wire mesh lagging, and over steel liner plates. A modern development that has been successfully used is to strengthen the shotcrete with the addition of 1-in. long by 0.015-in.-diam steel fibers, thus eliminating the need for wire mesh reinforcing (U. S. Department of Transportation (DOT), 1981). Advantages are faster, one-step installation, and less rebound. Most shotcrete systems can be handled by two men, but a high degree of skill is required to achieve satisfactory results.

479. Extruded concrete lining. A recent development in concrete lining is to combine the process with shield tunneling. Martin and Braun (1982) describe a 21-ft-diam shield machine which excavates at one end and extrudes a singleshell continuous steel fiber-reinforced concrete lining at the other end. This computer-controlled TBM was successfully used on a metro tunnel near the city of Frankfurt-am-Main in West Germany. The shield is a Wesfalia Lunen blade tunneling machine that accommodates the first of 12 segmental formwork rings and the concrete extrusion system in its tail section. There are separate sets of hydraulic rams for activating the steel blades of the shield's front and tail sections. A ring-shaped rubber seal prevents the pressurized concrete mix from leaking back into the shield. As the steel fiber-reinforced concrete is continuously extruded into the 8-in.-wide gap between the formwork ring and the tail ring of the shield, the pressurized mix fills the void between the formwork assembly and the excavated rock surface when the shield is jacked forward.

480. The extruded lining is confined between the steel formwork and the tunnel surface until the concrete mix has sufficiently hardened. The last of the segmented rings is dismantled and brought forward to be reassembled in the tail section of the blade shield. This procedure is repeated, being synchronized with the tunneling function of the machine. With this system settlements have been almost eliminated. The machine driver, positioned near the face, activates the blades, the excavator, and the spin conveyor as necessary to ensure the safe progress of the shield.

481. Final linings in soft ground tunnels are usually unreinforced concrete with a thickness of about 1 to 1-1/2 in./ft of finished tunnel diameter--a rule of thumb that has lasted many years. Because of the cost, mass concrete linings do not contain reinforcing steel, and they are usually put in place by slipforming with vibration compaction after placement of concrete.

482. Segmental linings. Precast concrete segmental linings have largely replaced steel segments and mass concrete linings. They are cheaper and quicker to erect allowing a faster driving rate for the TBM. Birkmyer (1975) reported that precast concrete segments may be manufactured for about one-third the cost of steel fabricated segments. Cost of concrete segments was reported to be very sensitive to the amount of reinforcing steel incorporated into the design.

483. The earliest form of segmental lining was brick. Brick suffers from several disadvantages, such as high labor costs for installation, insufficient curing time for the mortar to provide adequate strength in the short time interval between successive advances, and insufficient watertightness. Consequently, brick linings were replaced by liners composed of cast iron. These have gradually been replaced by concrete and structural steel units. Segmental linings are usually installed immediately after excavation and serve as both primary support and final lining.

484. Cast iron segments have traditionally been used in soft ground tunnels with groundwater problems. Segments are designed to be conveniently handled by one man and thus usually weigh between 60 to 70 lb, although segments weighing more than 150 lb are not uncommon. For TBM driven tunnels some form of mechanical aid such as an erector arm is usually provided behind the TBM in the tail of the shield, in many cases reducing lining erection to a one-man job, or two men working either side of the tunnel.

485. The outside faces of the four flanges of each segment are usually machined to ensure uniform bearing and asbestos caulk is applied to provide watertight joints after the rings are erected.

486. The disadvantages in the use of cast iron are its relatively high weight and unit cost.

487. Precast reinforced concrete segments have almost completely replaced cast iron segment linings. Innovative designs have been introduced with specially wedge-shaped segments, installed and expanded against the ground, thus using the passive pressure of the ground to eliminate the need for bolts between segments, and also eliminating the void left between the lining and the ground. Figure 61 shows expanded segmental linings in place.

488. There have been continual developments in both the design of and the material used for segmental linings, resulting in the selection of more economical designs and reduction in installation time. In soft-ground tunnels, the rate of advance is usually dependent on the rate of erection of the lining as the TBM shield must use the circumferential flange of the last erected ring of segments as a reaction for the hydraulic jacks to thrust the shield against the face. One method of reducing the segment erection time is to use longer and wider segments. However, experience suggests that use of any section that is heavier or longer than a man can handle may be counterproductive. This statement is based on the observation that sand hogs often erect the segments manually, even if an erector arm is available.

489. Cast-in-place concrete lining. Cast-in-place concrete lining is normally used as a final lining to provide protection for primary support, to improve flow characteristics or appearance, and to support the ground and water loads. Cast-in-place concrete lining is particularly useful as a final support system in tunnels which must resist large loads such as tunnels which are designed to resist nuclear blast effects. Cast-in-place linings are also used for reinforcing weak areas such as large tunnel intersections and large cavities.

490. The thickness of a concrete lining is governed by the ultimate load it must carry and by construction requirements. The thickness of the lining at the crown should be sufficient to provide room for the concrete placing pipe. This will seldom be less than 10 in. Where a thin lining is all that is required to carry the external loads, working room may be provided by excavating an enlargement in the crown.

491. Placement of cast-in-place concrete lining is normally accomplished by placing the invert pour first. The remainder of the lining is placed using collapsible forms. In some cases, two sets of forms are used. Concrete cures behind one set of forms while being placed in the next. Once the concrete is adequately cured, the form is collapsed and moved through the front form, expanded to the required shape, and concrete placed behind it.

Rock tunnel reinforcement and support methods

492. Reinforcement is used to enhance the ability of the rock to be self-supporting. Rock is quite strong if progressive failure along planes of low strength is prevented. It is the purpose of reinforcement to prevent this failure, thereby allowing the rock to support itself with its inherent strength.

493. In most civil engineering applications, the material strength of the intact rock is high relative to the expected stresses. However, rock is much weaker along joints and fractures. For this reason, deformation of the rock is generally controlled by the discontinuities. These discontinuities may be joints, bedding planes, foliation surfaces, shear zones, or faults.

494. Progressive deformation and relaxation may result in the collapse of a portion of the rock structure when shear stresses acting on discontinuities are only a fraction of the intact shear strength. In jointed rock masses, numerous factors determine the nature and extent of the rock mass deformation. These include the following:

_a_. The strength, deformability, orientation, and frequency of discontinuities.

_b_. The size, shape, and orientation of the excavation with respect to the discontinuities.

_c_. The method of excavation.

_d_. The state of stress in the rock mass surrounding the excavation.

_e_. The strength of the intact rock.

_f_. The groundwater pressure in the rock mass.

495. Rock reinforcement prevents or limits the deformation and dilation of the rock that may lead to collapse. The strength of the rock is maintained by the reinforcement. The primary reason for the success of rock reinforcement is the immediate restraint which reduces rock deformation, thus greatly enhancing the possibility of early stabilization following excavation. The shear strength of the discontinuities will always be less after separation has taken place. For this reason, the reinforcement should be installed as soon as possible after the excavation is made to minimize deformation and loosening of rock.

496. The advancing state of the art of rock reinforcement has now reached the point that it is always considered as an alternative or partial alternative to direct structural support of rock excavation. In its various forms, reinforcement is in common use on projects with opencuts, portals, tunnels, shafts, and large chambers.

497. _Rock reinforcement._ The design of reinforced rock structures follows the same basic steps used in the design of other structures. Excavations in rock are made in a material that is always under in situ stress and which generally is in stable equilibrium before the excavation is made.

498. In the design of rock reinforcement, the primary emphasis should be to guard against modes of deformation that may lead to collapse. Suitable construction procedures must also be considered as part of the design process and appropriate provisions made in the specifications to insure that design requirements will be met.

499. The first design efforts should be directed toward estimating the type and amount of reinforcement that might be required for a given project. At this point in the design the most useful information will be experience from similar jobs.

500. Although progress is being made in more completely understanding rock reinforcement/rock interactive behavior analytically, it is unlikely that the empirical approach will ever be completely replaced. The inability to predict such important factors as geologic conditions and engineering properties of the rock mass will undoubtedly foster the continued use of empirical rules.

501. As geologic and rock engineering information becomes available and as the plan of the project is finalized, detailed design of the reinforcement system may proceed. This detailed design has as its end product a set of plans and specifications which will indicate to the contractors what reinforcement the designer considers will be necessary to stabilize the rock structures. The design should include not only the number, length, size, and orientation of reinforcement elements but also excavation-reinforcement sequence and detailed installation requirements. The specifications should also allow flexibility in rock reinforcement requirements so that unanticipated geological conditions can be dealt with. No matter how detailed the geologic investigations may be, there will almost always be local conditions that cannot be foreseen and consequently will require additional reinforcement.

502. Rock bolting. When rock bolts are used as the principal element in a reinforcement system, the bolting operation becomes an integrated part of the excavation cycle. For drill and blast excavation this cycle is normally:

a. Set out a drill hole pattern for charging and bolting.

b. Drill charging holes.

c. Drill bolt holes.

d. Charge.

e. Install tensioned bolts.

f. Blast.

g. Ventilate.

h. Scale (and apply shotcrete if required).

i. Muck.

503. The equipment used to drill rock bolt holes is normally the same as that for drilling charge holes so there is no major problem in integrating these two activities. However, in case multiboom jumbos are used for drilling charge holes, jack-leg drills should always be available for drilling boltholes that cannot be reached by the jumbo.

504. If the integrated system is used for the organization of the actual support installation activities, a specialist support crew, led by a specialist in rock reinforcement, should be created. After each blast or advance round, the reinforcement specialist should examine the rock conditions, determine the reinforcement requirements and mark out the rock bolt drill hole positions as well as inclinations and lengths. A sketch indicating reinforcement measures should also be made as part of the construction record. The bolt holes are then drilled by the normal jumbo crew, immediately after drilling the blast holes, and the specialist support crew then moves in and installs and tensions the rock bolts. At a later stage, the support crew can return to retension and grout the bolts, and place wire mesh and shotcrete. All of these activities should be carried out under the close supervision of the support specialist who should carry sufficient rank such that he can stop the job if in his opinion, conditions are unsafe.

505. It has been found that this system can work very well if sufficient attention is paid to choosing the correct individual to lead the support team and clearly defining his responsibilities. Experience shows that there is minimal disruption of the overall cycle if the system is working correctly and rapid and safe advance can be achieved. The primary design considerations for rock bolting follow:

a. Rock block stability. In any excavation, the force of gravity cannot be ignored when considering the forces which act on excavation surfaces. Specifically, gravity is a direct contributor to stability or instability immediately around the surface of an excavation, depending on joint and fracture orientation and conditions. Unfavorable orientation of joints can cause individual rock blocks to loosen and become separated from the main rock mass.

b. Rock beam reinforcement. The earlier applications of rock reinforcement were mainly in mining work in sedimentary strata and gave rise to the concept that rock bolts created a beam or slab by clamping together a number of horizontal strata. Rock reinforcement creates a structural member in any jointed rock mass if a systematic pattern of bolts is used. The bolts, if tensioned, create a zone of uniform compression somewhat shorter in thickness than the length of the bolts. Where untensioned grouted rebar is used instead of tensioned rock bolts, the reinforcement develops only after limited deformation has taken place.

506. The length of the rock bolts is dependent not only on the geological features of the rock near the surface but also on the span of the opening.

The structural member created by the bolts should be relatively deep compared to the span and the depth of this member depends on bolt spacing as well as length. Due consideration must be given the type and condition of the rock that is being reinforced.

507. In cases where the occurrence of persistent well-defined joints requires the use of relatively long bolts, it may be feasible to use a smaller number of these and provide shorter supplementary rock bolts between the longer bolts. This method creates a more heavily reinforced zone near the surface and is effective in stabilizing fractured rock.

508. Tensioned rock bolts. The use of tensioned reinforcement elements is included in most rock reinforcement systems. The desired result of a tensioned rock bolt installation is a permanently tensioned reinforcement element with positive bond to the rock. Basic areas of concern in tensioned rock bolt installation are:

a. Obtaining anchorage.

b. Tensioning to the desired prestress.

c. Locking the prestress.

d. Protecting against loss of anchorage and corrosion.

509. Each area of concern is critical to a good permanent reinforcement system. A number of hardware types, techniques, and bonding materials have been used to achieve the desired installation. This selection of specific rock bolt hardware, grouting material, and installation method is often the result of personal experience of the design engineer as well as the result of cost studies. However, even the most highly proven techniques may fail to give satisfactory results if careful attention to detail is not practiced during installation.

510. There are two types of anchorage in general use. These are mechanical anchorages and grouted end anchorages. The mechanical types make use of an expanding element that is forced against the walls of the borehole to deform the rock and to provide frictional resistance to pullout. Grouted end anchorages rely on a bonding medium between a portion of the reinforcing element and the rock to develop the desired anchorage strength. Combinations of grouted end and mechanical anchorages are also possible, but are not generally used because installation techniques are more complicated and time-consuming. Regardless of the anchorage type used, subsequent full-length grouting after tensioning improves the reinforcement capability of the element and protects it against corrosion.

511. Two methods of tensioning bolts, independent of the type of anchorage used or the type of bolt used are: direct pull tensioning using a hydraulic system and torquing of the nut using a torque wrench. Direct pull tensioning has two advantages over torquing. The first is that torsional stresses combined with tensile stresses reduce the strength of the bar. The other advantage is that direct pull tensioning gives a positive indication of the capacity of the anchorage within the range of the tensioning load for every bolt installed.

512. Determination of anchor capacity in a particular rock type must finally be determined by conducting field pull-out tests at the site.

513. Untensioned reinforcement elements. Although the installation of tensioned fully grouted elements is preferred for rock reinforcement, some conditions may make the installation of fully grouted untensioned elements (commonly referred to as rock dowels) desirable. Once installed, stress is developed passively in the element as rock movements take place. Installation of grouted untensioned elements may be necessary when it is difficult to achieve anchorage for tensioning. Other uses are for spotbolting areas that are essentially stable. Installation techniques and grouting materials are identical to those described for forming grouted end anchorages or for full-length element grouting.

514. Other methods involve the use of compressed air to force plastic portland cement mortar into the drill hole. The element is then inserted to force excess mortar to flow out the hole.

515. Untensioned elements of all types may be installed without hardware at the face depending on the application. Nuts tightened against bearing plates are important for providing restraint and to prevent loosening of surface rock. Threaded bar ends are also needed for fastening wire mesh or other surface treatment, when used. Where surface rock is highly fractured but temporarily stable, unthreaded bars could be installed followed by a shotcreted surface treatment. On the other hand, shotcrete might be used to provide initial support and reinforcement installed through the shotcrete. In this case, bearing plates could be installed at the surface to increase the support capability of the shotcrete.

516. High-capacity tensioned rock anchors. Long high-strength cable and rod-type bolts have been used in a number of cases to solve special rock reinforcement problems. Systems are made up of wires, strands, or rods.

High-strength reinforcement systems all have three basic features: (a) an anchoring device, (b) a tensioning device, and (c) a tendon or bar connecting these two. The available systems differ mainly in the gripping or holding mechanisms, which are normally patented. The length of grouted anchors may be 30 ft or more depending upon local rock conditions, capacity of the anchor, and the drill hole diameter. Tensioning of high-capacity reinforcement systems is accomplished using hydraulic jacks. The transfer of the load from the connecting element to the bearing plate is accomplished by three methods: button heads, wedge grip, and threads.

517. Shotcrete. Shotcrete and composite reinforcement/support systems that include shotcrete are today very widely used in underground openings. Current design practice is based on conceptual considerations and on case histories with shotcrete, as reflected in literature and in the designer's own experiences. There are two basic types of shotcrete. Dry-mix shotcrete, as the name implies, is mixed dry and the water is added at the nozzle. Wet-mix shotcrete is mixed as a low slump concrete which is then pumped to the nozzle. In the case of the dry-mix, accelerator can be added to the mix but, in the case of the wet-mix process, it must be added at the nozzle.

518. Shotcrete is quite versatile and has the following uses:

a. Shotcrete can minimize water and gas flow due to its low permeability. Shotcrete is frequently used as a water stop during construction and is not specifically designed for this purpose. Shotcrete can be applied directly on surfaces through which distributed "area" flow enters the tunnel.

b. The Bernold method consisting of perforated corrugated steel sheets backfilled with concrete requires a shotcrete protection of the steel sheets. Steel sets that would be exposed for a long period of time can also be protected by shotcrete in a 1- to 2-in. thick layer. Although mainly intended for corrosion prevention, shotcrete contributes to the structural support performance in all these applications and may thus be included in the design.

c. A thin protective coating of shotcrete, 2 to 3 in. thick, can be sprayed on the roof and walls to prevent deterioration or loosening of exposed rock blocks.

d. Shotcrete, typically unreinforced shotcrete 2 to 4 in. thick, can be used to provide light support.

e. Shotcrete, normally 4 to 6 in. or more thick, can be applied over wire mesh or reinforcing steel bars, with rock bolts, to provide moderate to heavy support. Fiber-reinforced shotcrete, using small steel fibers mixed with the shotcrete, can eliminate the need for mesh reinforcement. Advantages of

> fiber-reinforced shotcrete are less rebound and less time required for application (reinforcement is not separately placed before spraying).

519. When an opening is excavated in rock, under certain conditions elastic as well as permanent deformations will take place. The deformations are time-dependent both as a function of the advancement of the excavation and as a function of the time-dependent characteristics of the rock mass as a material. As the deformations occur, the inherent available rock mass strength is reduced because of strain softening and loss of confinement.

520. Therefore, the most efficient way of stabilizing a blocky rock mass is to reduce the deformations and maintain rock arch continuity. Rock bolt reinforcement can effectively reduce these time-dependent deformations. Steel sets or concrete lining can arrest the deformations, but are less efficient than rock bolts.

521. It is difficult to envision how thin (2- to 4-in.-thick) shotcrete can reduce deformations and maintain rock arch continuity. A layer of 2- to 4-in. shotcrete does not entirely support the rock mass, but forms a stable, composite rock mass/shotcrete structure. The essential effect of shotcrete used this way is to prevent "key" blocks from loosening and thereby causing loss of rock arch continuity.

522. Tensile and shear strengths of the shotcrete and rock are important, but the shotcrete/rock adhesion strength is of greatest significance. The most difficult adhesion problems exist when the rock blocks are separated by discontinuities with coatings of clay, chlorite, talc, or serpentine.

523. Reinforcing mesh can greatly improve the efficiency of shotcrete and is commonly specified for tunnel projects. The major objective of mesh is to provide tensile reinforcement.

524. The empirical approach is the basis for design of composite systems involving rock bolts and reinforced or unreinforced shotcrete.

525. Shotcrete has sometimes found use as a substitute for a conventionally placed concrete liner with a thickness of 6 in. or more. It can be used in combination with steel sets. Shotcrete has been extensively used to control "area seepage" (directing the flow of water through weep holes in the exposed surfaces, in contrast to the concentrated flow from channels) by applying an impermeable coat and providing relief or weep holes. Recently, concentrated flows have been handled by shotcreting surfaces, together with preinstalled drains and relief pipe.

526. Shotcrete alone reacts in the same manner as any reinforced or plain concrete by supporting stresses due to bending, thrust, and shear. The differences in shotcrete technology, relatively lower strength and lower unit weight compared to regular concrete, have no effect on the basic mechanism. The usually faster setting time and strength increase of shotcrete compared to concrete allow application to steep and vertical faces and also to overhanging faces without the need for forms.

527. Shotcrete interaction with the ground involves several mechanisms:

a. The shotcrete adheres to the ground by a combination of shear and tensile stresses between the ground and the shotcrete and within the shotcrete.

b. The shotcrete fills openings (fractures, joints) in the ground adjacent to the application surface. This permits a transmission of compression, shear, and tensile stresses across these discontinuities.

c. These two characteristics, adherence to the ground and filling of discontinuities, makes it possible to transmit shear stresses with little or no slippage between shotcrete and ground and also to transmit tensile stresses. The shotcrete and adjacent ground thus behave as a composite structure.

d. Individual rock blocks or plastic zones in the ground move or deform and may shear through the shotcrete. This shearing mechanism is the same that any normal concrete structural member may undergo; it is mentioned specifically due to its importance in tunnel support design.

e. One of the most important shotcrete characteristics is the ductility or flexibility, particularly of thin shotcrete layers used for tunnel support. The flexibility is not only due to the use of thin layers but also due to the fact that the shotcrete acts structurally immediately after setting. The flexibility in bending becomes relatively unimportant compared to thrust and shear.

f. The usually uneven ground surface, particularly in a blasted tunnel, leads to an equally uneven shotcrete layer. This increases the moment of inertia of the shotcrete layer if it is considered independently of the ground. This unevenness increases the aforementioned interlocking effect. Also, the effective thickness of the shotcrete increases due to the inclined surfaces. The effect of the protruding edges and corners is somewhat disputed. Some engineers state that these are the locations of the first fractures because of tensile stress concentration and usually thinner shotcrete. Several European engineers, however, have made the point that the protruding surfaces in a blasted tunnel are obviously more resistant and therefore need less support.

528. Shotcrete mix design. The overall approach to mix design is similar for both wet- and dry-mix processes, but there are some important differences in detail depending upon which process is used. In either process, the mix design must satisfy the following criteria:

- a. Ease of application. Must be able to be placed overhead with minimum rebound.
- b. Early strength. Must be strong enough to provide support to the ground within 4 to 8 hr after application.
- c. Long-term strength. Must achieve a specified 28-day strength with the dosage of accelerator needed to achieve good application and early strength.
- d. Durability. Long-term resistance to environment.
- e. Economy. Low cost of materials and minimum losses due to rebound.

529. Selection of materials. The following comments apply to the selection of materials typically used in shotcrete:

- a. Portland cement. Type I portland cement is most widely used in shotcrete applications since it is the most readily available type and it satisfies most of the normal shotcrete requirements.
- b. Aggregates. Natural gravels are preferred over crushed stone because of the better pumping characteristics of the rounded natural aggregate particles. Otherwise, the quality of aggregate required for shotcrete is the same as that for good quality concrete.
- c. Water. Water used in shotcrete should meet the same standards as that used in concrete.
- d. Accelerators. When a rapid gain in the early strength of shotcrete is required to provide immediate support to the rock, accelerating admixtures or accelerators are added to the mix. The addition of accelerators can also be used to improve shooting conditions and to reduce rebound, particularly when working overhead.
- e. Mix proportions. A typical shotcrete mix contains the following percentages of dry components:

cement	15-20 percent
coarse aggregate	30-40 percent
fine aggregate or sand	40-50 percent

The water-cement ratio for dry-mix shotcrete lies in the range of 0.3 to 0.5 and is adjusted by the nozzleman to suit local conditions. For wet-mix shotcrete, the water-cement ratio lies between 0.4 and 0.6.

530. Placement of shotcrete. The quality of placed shotcrete depends on the materials used and the mix design, as discussed above, but is also

heavily dependent on the method of placement. In particular, the skill of the nozzleman in preparing the surface, controlling the delivery rate and thickness and, in the dry-mix process, the water-cement ratio, has a significant influence on the final product.

531. Preparation of the surface to be shotcreted is an essential part of the shotcreting operation. Effective scaling is important for the safety of the operators and also to reduce the chances of "drummy" shotcrete caused by spraying onto loose rock. Obviously, if the rock is of very poor quality, scaling may not be possible and the shotcrete may have to be applied as quickly as possible after exposure of the rock face to provide support. In such a case, a second shotcrete layer, reinforced by means of wire mesh, may be required to complete the treatment of the surface.

532. Surfaces to be shotcreted should be free of all loose or foreign matter if a proper bond is to be obtained. Dust from the blasting operation and gouge from the rock joints should be washed off the surface and this is most easily achieved by jetting the surface with an air-water mixture.

533. The optimum distance between the nozzle and the surface being shotcreted is approximately 3 ft. The amount of rebound is significantly influenced by this distance. Rebound is also influenced by the angle of the nozzle to the surface. The nozzle should be held perpendicular to the rock surface.

534. The thickness of a shotcrete layer is generally estimated from the volume of material placed with an appropriate allowance for losses due to rebound. When spraying very irregular surfaces it is almost impossible to achieve a uniform thickness and it may be necessary to apply more shotcrete than originally planned to insure that all the rock is covered. When wire mesh reinforcement is attached to the rock face, this mesh can be used as a gauge for shotcrete thickness.

535. Wire mesh and shotcrete. Wire mesh is commonly used for reinforcing shotcrete and it consists of a square grid of steel wires, welded at their intersection points. Generally, wire mesh is attached to the rock by means of a second washer plate and nut placed on each existing rock bolt. Intermediate anchorage is provided by means of short bolts or mesh grips. The wire mesh steel will suffer from corrosion if it is not fully encased in shotcrete. A minimum shotcrete cover of 1 in. is required to prevent corrosion.

536. Fiber reinforced shotcrete. One of the disadvantages of normal shotcrete is its low tensile strength and it is not uncommon to see shotcrete which has been severely cracked by movements in the rock mass after the shotcrete has set. Wire mesh reinforcement can be used to overcome this problem but the installation of the mesh is a time-consuming and therefore expensive operation. The idea of mixing steel fiber reinforcement directly with the shotcrete during application has attracted a great deal of attention and research during the past decade.

537. Much of the early experimental work involved mixing 1-in.-long by 0.1-in.-diam steel wires with the cement and aggregate in proportions of 3 to 6 percent by weight. Higher fiber contents were found to be difficult to mix and to shoot. Difficulties with balling of the fibers and rebound losses of up to 60 percent have been reported. More recent work involving mixing the shotcrete and the fibers at the nozzle appears to reduce fiber losses to about 15 percent and to reduce the problem of fiber balling.

538. Shotcrete as a reinforcement measure is extensively used today. After more than 25 years of use and experience in underground construction, shotcrete today is regarded as a complete and totally satisfactory final reinforcement system. As an example, mesh reinforced shotcrete with a thickness of 2.5 in. in conjunction with systematic roof bolting is considered sufficient roof protection in civil defense centers in Finland.

Shaft Lining and Support Systems

539. Shafts may be lined with concrete using precast segments, cast-in-place concrete, slipformed concrete, gunite, or shotcrete. Steel sets and wood square-sets are used for support. Rock bolts are sometimes used to provide initial support before permanent support or a lining is installed.

540. Nearly all modern shafts are lined with concrete to provide support, to seal out excess water, and to protect the wall rock from deterioration. The thickness varies but is commonly 1 ft. Placement of the lining may be done in stages following shaft sinking, concurrent with sinking, or by alternating with excavation.

541. Shallow-to-medium depth shafts in competent rock can be lined after excavation. This practice allows more rapid sinking and lining of the shaft because the two operations do not interfere with each other.

542. If lining is to be installed concurrently with sinking operations, two work crews are required; one sinks the shaft while the other places the lining. A large work force and complex equipment arrangements are required. Close supervision and careful planning are essential.

543. Methods for rapidly lining shafts include using precast concrete segments, modified jump-forming, continuous slip forming downward, and shotcreting. All of these rapid lining systems include elaborate water-control measures, ranging from pregrouting to water rings, such as shown in Figure 62, to collection and ducting for heavy inflows. Seepage can be a major problem under freezing conditions.

544. Timber support and lagging. Most older shafts in the United States have used square-set timbering for support. Spacing and size of the sets are determined by ground conditions, and the timbers have the flexibility to control heavy ground or unstable ground with no major problems. Concrete can be added behind the sets if ground control problems are extreme. Disadvantages include high cost in areas where wood is in short supply, short life-span due to dry rot, low strength, and the danger of fire. Timbered shafts usually include a poured concrete collar, and a shaft-bearing set should be installed at regular intervals of 250-300 ft, depending on ground conditions, to provide stability and support to the timbers. Timbers are usually hung from the preceding set with steel hanging rods, blocked, and squared. Lagging, if any, is placed around the shaft.

545. Cast-in-place concrete lining. Circular concrete-lined shafts are becoming more prevalent. Concrete is adaptable in that it can be varied in thickness, used to fill voids, is fireproof, easy to install, relatively inexpensive and maintenance free, and provides a smooth liner with adequate water control options. Most United States shafts are lined during the excavation cycle in steps. Forms are lowered and bolted to inserts in the bottom of the previous pour, and then to a curb ring placed at the bottom of the section to be lined. Concrete is mixed on the surface and delivered through a slick line to a remix station, and then to the forms through hoses. Cables, guides, dividers, and other items are cast into the concrete. The bottom edge of the last pour is usually inclined upward to the inside to aid in providing a tight joint with the next pour.

546. In response to a 1977 Bureau of Mines contract, two designs were developed to continuously line a large-diameter shaft behind a boring machine.

One used a modified jump-form system (see Figure 63), making pours of 5, 10, or 15 ft with a very high-early strength concrete (Halter and Eklund, 1978). The form was made of nine interlocking panels, two of which were joined by hydraulic cylinders which provided pressure against the shaft wall or contracted the liner to allow it to move downward. Concrete was to be mixed and delivered from a separate galloway stage over the form, which was supported by an intricate curb ring assembly. The entire system was to be suspended from the surface by wire rope from a specially built headframe. This concept, still in the design phase, was to be capable of lining a 3,000-ft shaft in less than 8 weeks at an estimated cost (1978 dollars) of $874 per vertical foot.

547. Steel sets and lagging. Steel sets consist of steel rings, assembled in pieces, and can include a clamp with a hydraulic jack to provide immediate support to the shaft wall. Steel sets are faster to install and easier to align than wood sets. They are bolted together with lagging placed in the web. This method is very effective in preserving the structural integrity of the shaft. Steel segments may be welded together to form a watertight liner. In such cases the liner must be designed for the full hydrostatic head.

548. Precast concrete segmental lining. Precast concrete panels reinforced with fiberglass have been tried in Germany and the United Kingdom (Grieves, 1981). Lightweight and strong, these panels are installed using the frame of the raise borer. A complete ring is assembled on the deck, raised into place, and attached to the shaft wall by an injection of grout into the void behind the liner. This method has proven simple, economical, and uses relatively little manpower. A Bureau of Mines contract in 1977 resulted in a similar design (shown in Figure 64) using precast concrete segments 12 in. thick to line a shaft 24 ft in diameter (Dravo Corporation, 1978). This system, operating on a rather elaborate thrust-ring assembly, was designed for use with a continuous boring machine. Although still in the design phase, this concept was to be capable of lining a 2,000-ft shaft in less than 8 weeks, at a cost (1978 estimate) of $1,056 per vertical foot. This system included a subsystem for the continuous extension of its service lines as well as those used by the boring machine, and detailed plans were made for dealing with water, voids, and other problems.

549. Slip-formed concrete lining. Another design, developed under the same Bureau contract, used an inverted slip-form to line the shaft, as shown in Figure 65 (Wallhagen, 1978). This design was selected for laboratory and field testing. Performance specifications for this system included the ability to line blind-drilled, downhole bored or raise-bored shafts 12 to 26 ft in diameter, to depths of 400-2,000 ft. A minimum liner strength of 3,000 psi was desired with a capability to vary the lining thickness from 10 to 18 in. Plans to handle voids, slough zones, water-bearing regions, and extended work stoppages were included in the design. Lining rates were to be 1 to 5 ft/hr and average 50 to 100 ft/day, at targeted costs of approximately $800/ft for a 12-ft-diam shaft, and $1,750 for a 25-ft-diam shaft (Torbin, 1982).

550. The continuous shaft lining system (CSL) is composed of three main parts: a slip-form, curb ring, and jack frame. It can operate in three modes: continuous slip-forming, mechanized step-forming, and jump-forming. The jump forming is used primarily to deal with problem zones. Preliminary costs (1978 estimate) indicate a total cost per foot between $700 and $1,000, with operational costs roughly twice the cost of equipment (Wallhagen, 1978). It was estimated that four 2,000-ft shafts could be lined before major components would have to be replaced. Phase I of the contract, construction and testing of a full-scale test facility, has been completed and plans are underway for an underground test.

551. Remote-controlled shotcrete lining. The remote-controlled shotcrete lining system shown in Figure 66 is becoming more popular for shaft lining. It uses a remote-controlled shotcrete nozzle to line a predrilled 9- to 12-ft-diam shaft at rates up to 60 ft/hr (Monaghan et al., 1977). A system developed under contract to the Bureau of Mines uses a three-section stage, suspended from a headframe, with a rotating nozzle at the bottom that sprays shotcrete onto the shaft wall. Concrete is delivered in a dry mix from the surface through a 2-in.-diam steel pipe. Water and an accelerator are added at the nozzle. The entire system is operated on the surface from a control center in the headframe. Progress is monitored by a closed-circuit television camera mounted on the stage. The operator has the flexibility to change the rate of descent or rotation in order to vary the thickness of the liner when slough or fallout zones are encountered. These areas are inspected with the television camera before each 21-ft section of liner is applied.

552. The remote-controlled shotcrete system has been field tested (with over 2,500 hours of use) and modified to correct weaknesses. A 12-ft-diam shaft was lined to a depth of 850 ft in 1981. This project was completed in 34 days, including mobilization and demobilization, and experienced only 3 hr down time. Costs were approximately $77 per linear foot (V. Valencia, International Ground Support Systems, telecon, Aug. 1981). Although this system is presently limited to predrilled raises and shafts, it probably could be adapted for use with a continuous borer by applying a protective layer of shotcrete to the shaft wall during sinking, and lining it completely after the shaft is completed.

Summary of Tunnel and Shaft Support Methods

553. Support may be provided to stabilize the tunnel opening using any of several methods. Support design is largely empirical. Versatile support design is based on use of a single support method throughout the tunnel that is capable of supporting the excavation under the worst conditions expected. Adaptable support design is based on use of a range of support measures, keyed to the rock conditions expected in each zone. Versatile support is more conservative in the zones of better rock, and hence, more costly for material. However, only one support system must be stockpiled and the crew quickly becomes proficient in installing a single system. Adaptable supports require stockpiling of several support systems and crew efficiency decreases after every change. However, material costs will be lower.

554. Soft-ground support systems include steel ribs and lagging, cast-in-place concrete, precast concrete segmental lining, cast iron segmental linings, and steel segmental or rolled plate liners. Shotcrete has also been used and extruded concrete linings have seen limited use. Cast iron and steel are very effective liners but cost far more than concrete. In most cases, cast-in-place concrete and precast linings belong in the category of versatile support, i.e., they are designed for the worst conditions and are overconservative throughout the rest of the tunnel. Shotcrete is quite adaptable, but if a single thickness is specified in the contract, the advantage of adaptability is lost. Shotcrete may be used effectively and economically to seal the surface, to protect steel support, to prevent initial deformations and loosening, or as a complete support system. Because of their high cost, cast iron

and steel liners are only used under special conditions. Concrete can be used effectively for a range of ground conditions, from thin precast segments for aesthetics or improved flow properties, to thick cast-in-place linings to carry heavy loads and resist earthquake or blast damage.

555. Rock support systems include rock reinforcement and direct structural support. Rock reinforcement may consist of rock bolts, dowels, or anchors, and shotcrete. Steel ribs and lagging or concrete, either cast-in-place or precast segments, may be used for direct structural support. Rock reinforcement design is based on the concept of limiting deformations to take advantage of the rock's self-supporting ability. Rock bolts and/or shotcrete may be installed close to the face to limit deformations and this practice is recommended. Rock bolts and shotcrete are readily adaptable to changing conditions. Concrete linings must be installed some distance back from the face, which can result in problems in bad ground. Steel sets and lagging may be installed near the face in blasted tunnels. They are adaptable by varying spacing and support weight. Rock bolting and shotcreting can be integrated into the excavation cycle for TBM or conventionally excavated tunnels and should be placed under the control of a support specialist for best results. Installation of precast or cast-in-place linings may also be integrated into the excavation cycle for TBM-driven tunnels.

556. Nearly all shafts require support, which is usually provided by timber, steel, or concrete. Nearly all modern shafts are lined with concrete because it not only provides support but helps control groundwater and protects the wall rock from deterioration. More recently, shotcrete and concrete segments have been used. Welded steel liners are very effective in providing structural support while preventing water inflow, but their cost is high. Shallow shafts or deeper shafts in competent rock can be lined after sinking, but most are lined concurrent with sinking.

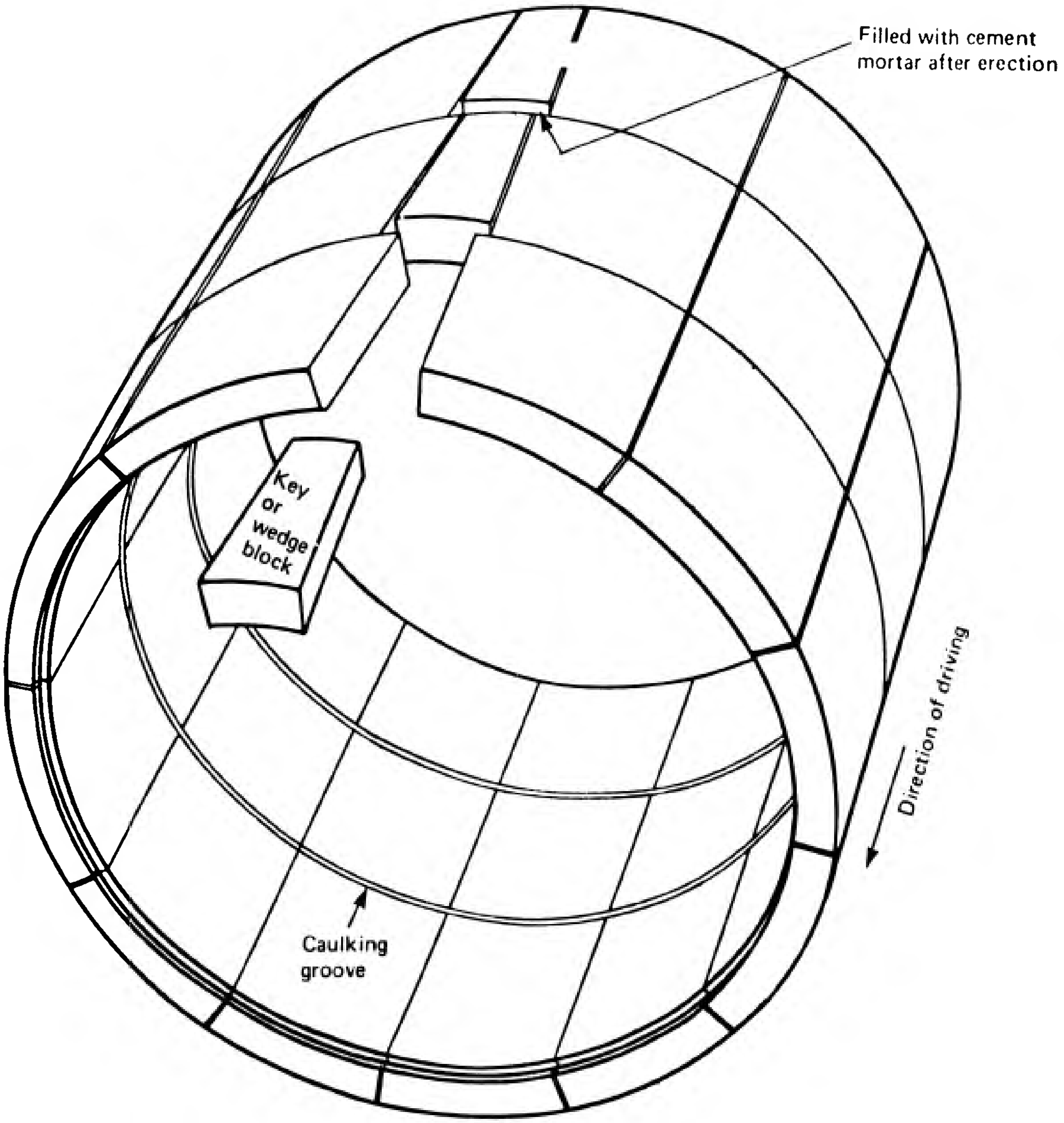


Figure 61. Wedge block expanded concrete lining (from Craig and Muir Wood, 1978)

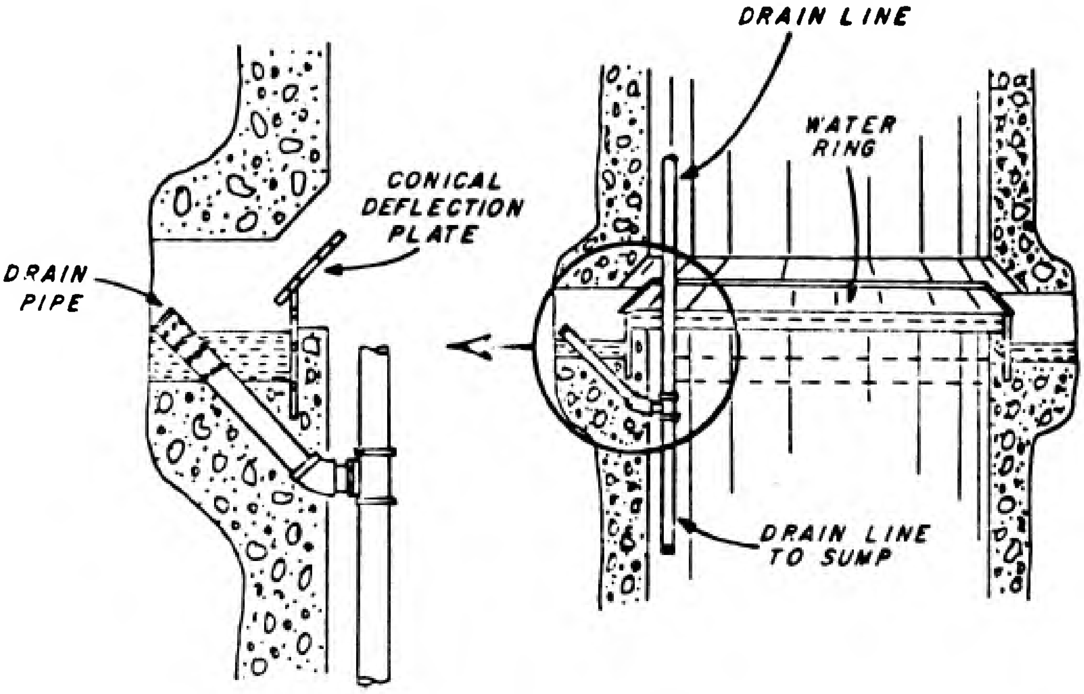


Figure 62. Detailed section of water ring (after Stevens, 1973)

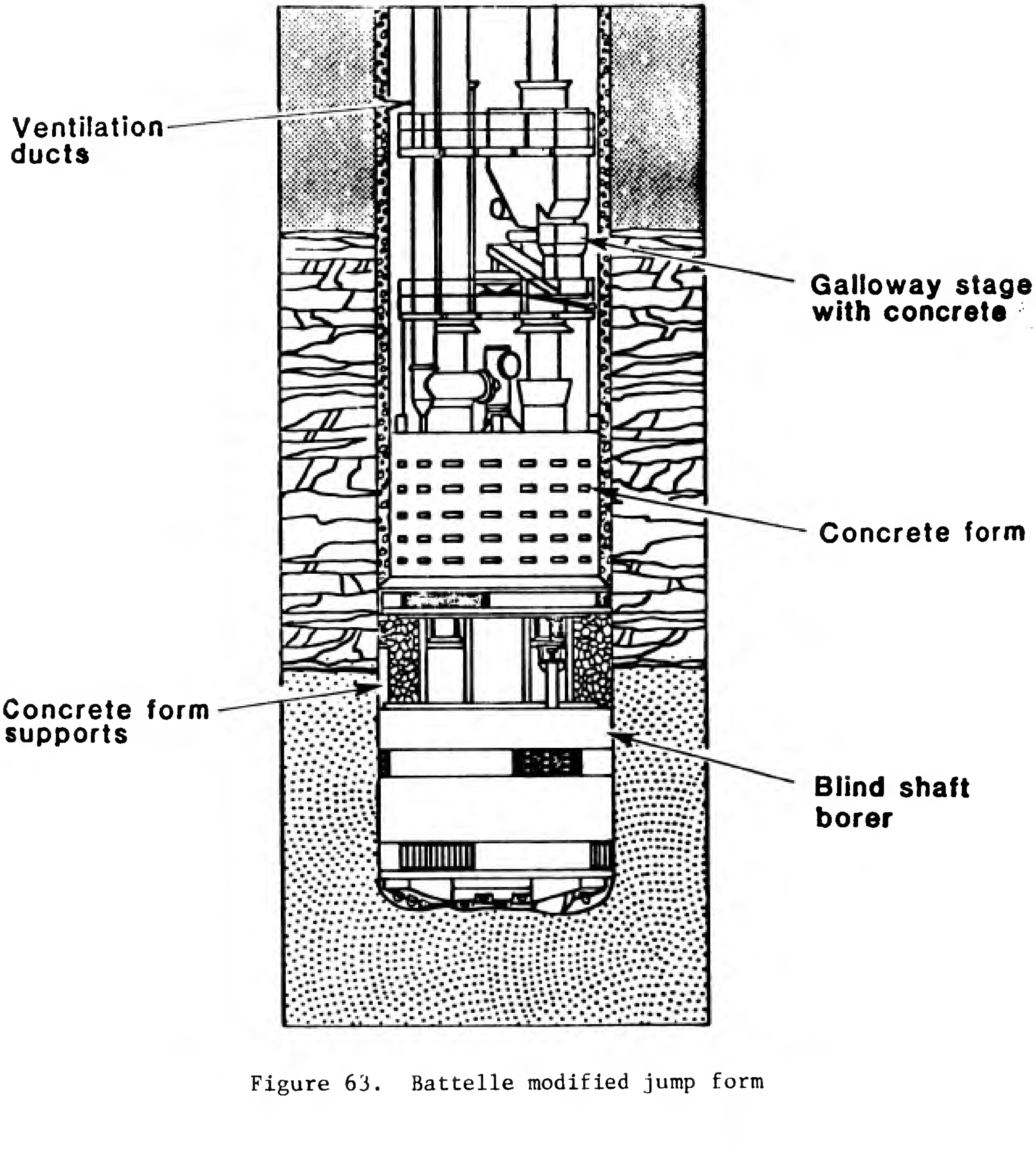


Figure 63. Battelle modified jump form

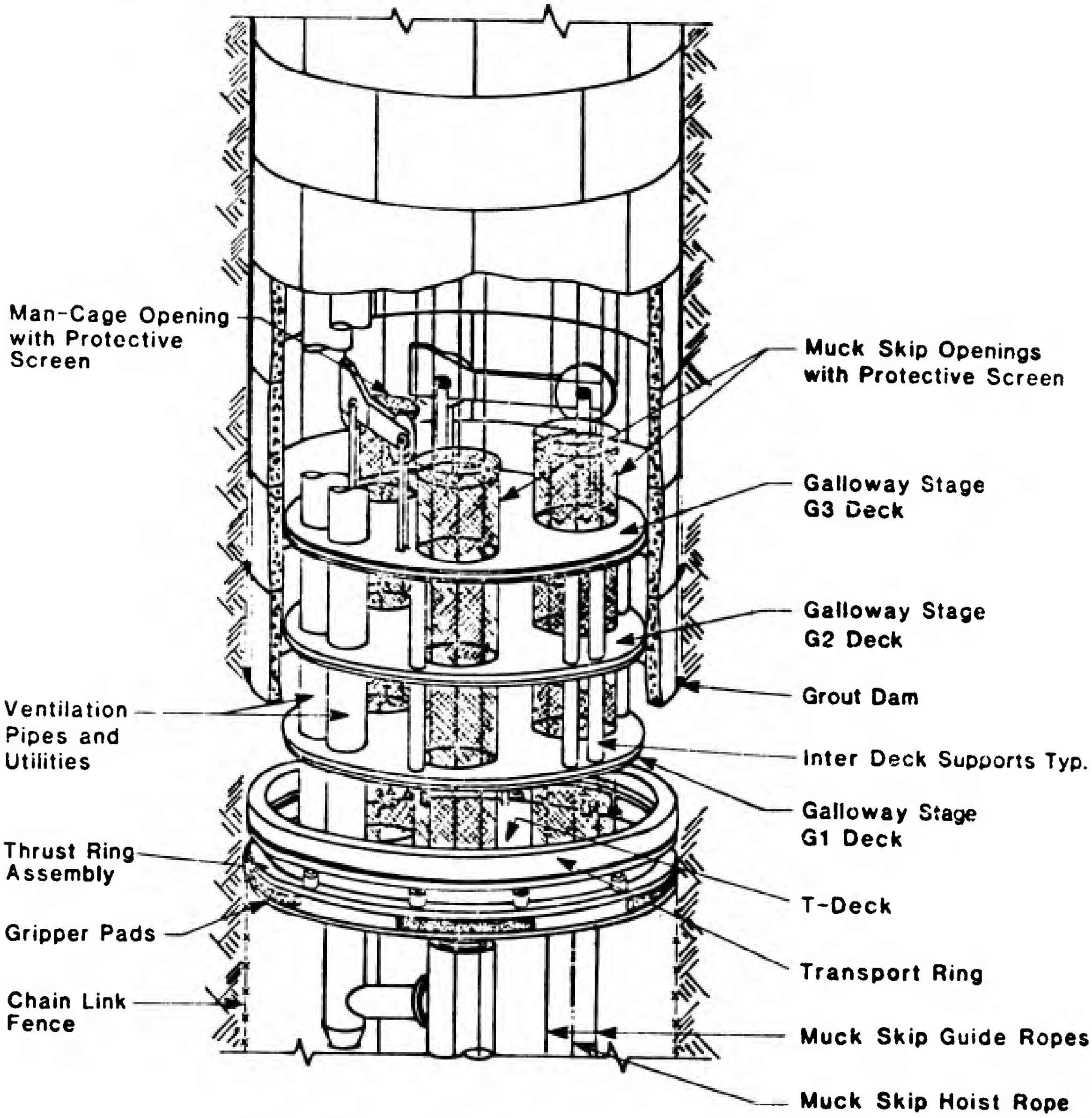


Figure 64. Dravo thrust ring and galloway

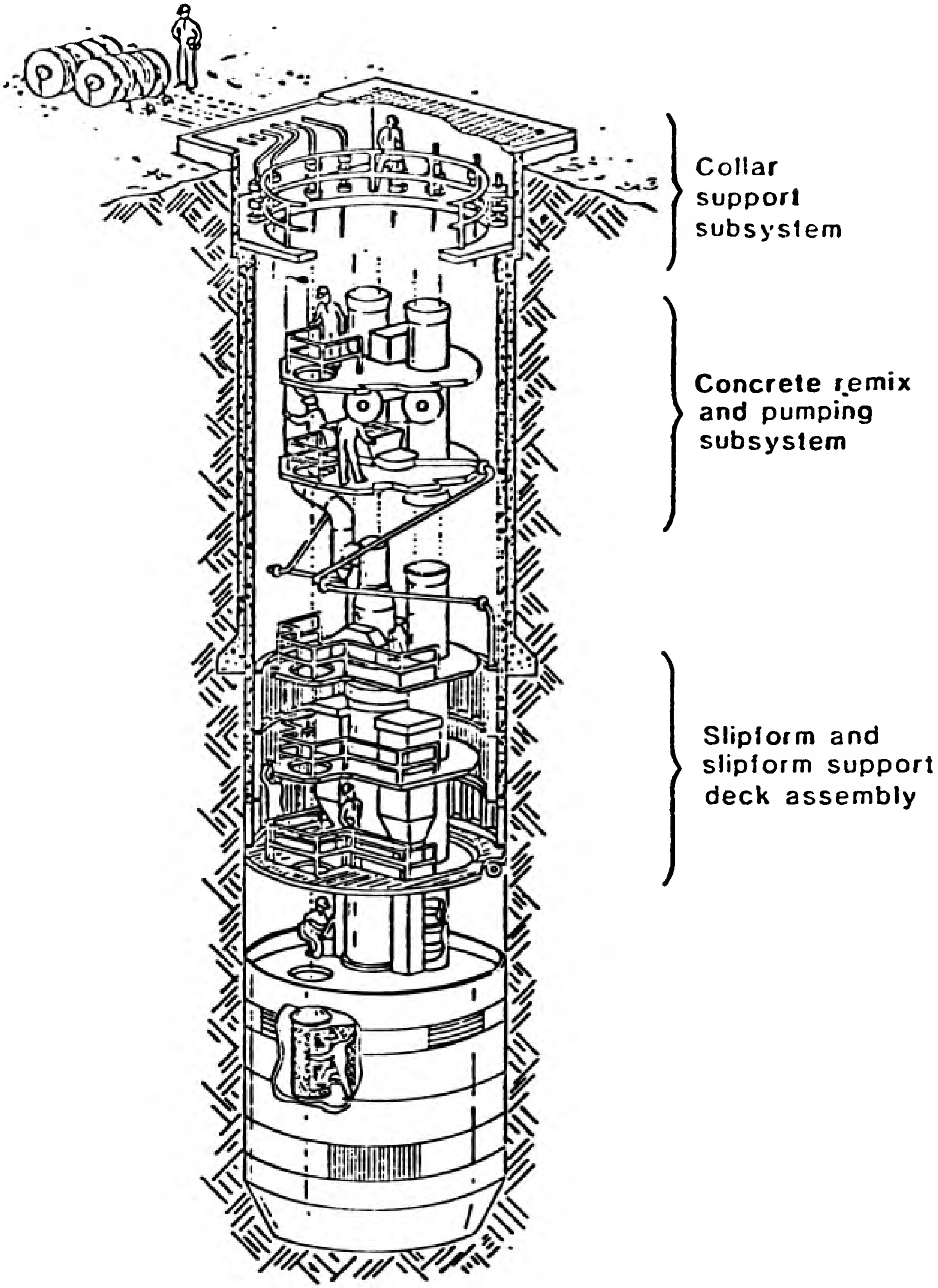


Figure 65. Rapidex inverted slip form for lining large-diameter shafts

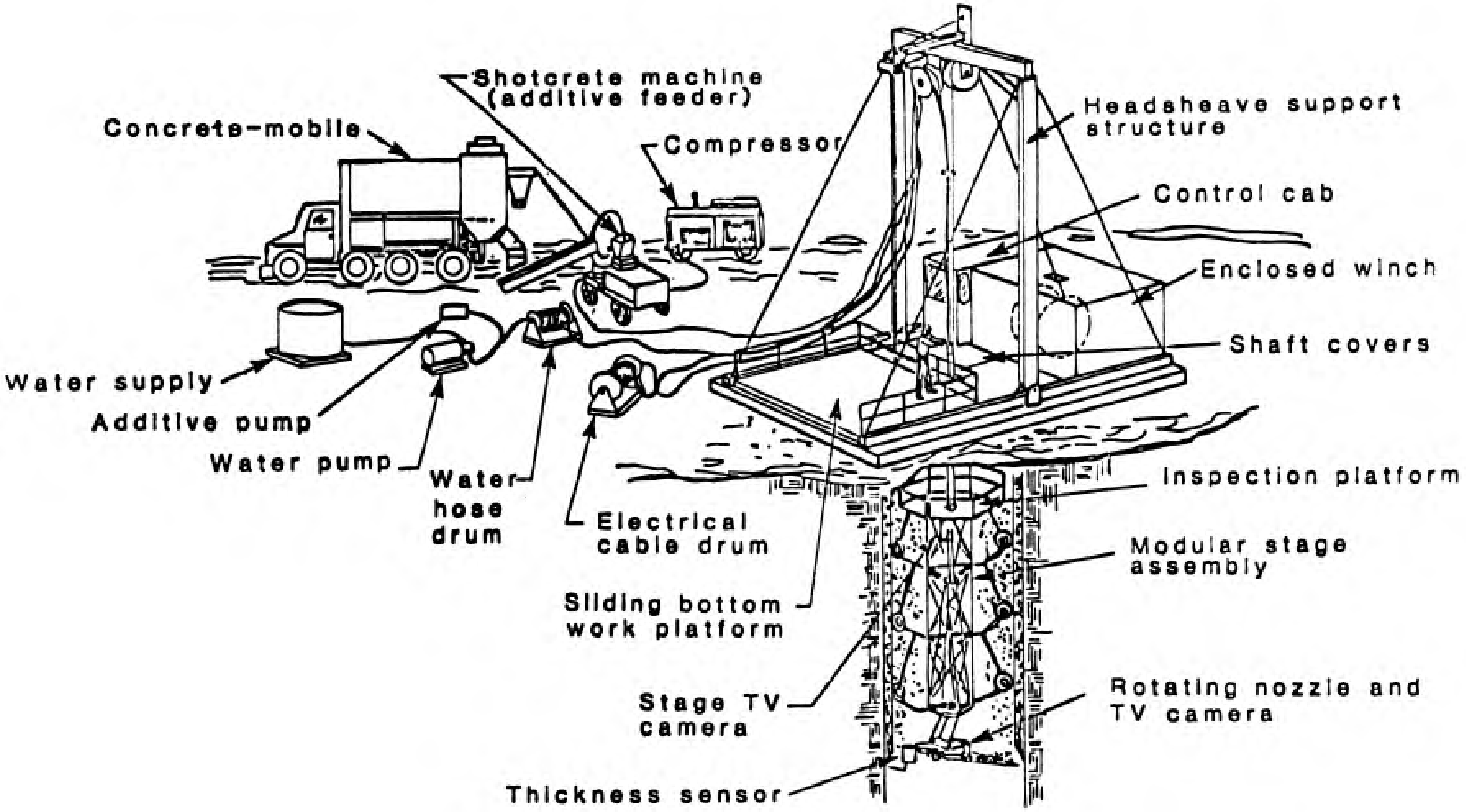


Figure 66. Shotcrete lining system

PART VI: GROUND STABILIZATION AND GROUNDWATER CONTROL

557. In some cases, the ground conditions along the route of a tunnel may be so unfavorable that excavation cannot proceed without measures being taken to control and improve the ground. Such conditions are encountered in tunnels below the water table in flowing ground or in tunnels in soft clay where the stability of the face cannot be insured. These conditions may prevail over long sections of the tunnel or occur only in localized areas.

558. When ground stabilization is required, the specific solution will depend upon the type and extent of adverse ground conditions, the proximity of the tunnel to adjacent buildings and services and the possibility of repetition of similar conditions on other sections under the same contract. The following methods are available to overcome adverse ground conditions and inflows:

a. Groundwater lowering by pumping.

b. Grouting.

c. Freezing the groundwater.

d. Using compressed air.

559. While all of these methods are applicable in flowing ground, in most cases only compressed air can be used to reduce the problem of face stability of tunnels in clays.

560. A common feature of all methods of groundwater control is high cost. This cost can be kept within reasonable limits if the potential problems and necessity of groundwater control are recognized during the design stage. Costs can, however, become prohibitive if the difficult conditions are not expected prior to construction since the method of control could be incompatible with the actual tunneling or lining method and much time may be lost in getting through the difficult zone.

Groundwater Lowering by Pumping

561. Groundwater lowering is the process of controlling the groundwater prior to the start of the excavation. In shallow tunnels, this can be accomplished by the installation of a deep well or wellpoint system to draw down the water table below the tunnel invert elevation. Once the water table has been lowered, the pumping system must continue to operate until the final

watertight lining has been constructed. Dewatering to depths of as much as 100 ft can be carried out by using eductor well-points, but the power requirements increase substantially as the depth increases. It may be more economical to go to other forms of groundwater control such as deep wells.

562. Groundwater lowering, unless carefully executed with appropriate filters, can remove fines from the soil, thus leading to possible subsidence. This subsidence would be in addition to any that might occur in compressible deposits due to the self-weight consolidation of the soil as water is removed from the voids in the mass. Since the zone of influence of the dewatering process can extend for a considerable distance on either side of the installation, it is necessary to monitor the width of the zone of influence to be forewarned of the possibility of settlements of adjacent structures. Groundwater lowering can be used in soils from gravelly sands down to the fine sand range as long as suitable filters are used to prevent movement of sand. In fine-grained soils, gravity flow of water becomes slow and can be speeded up by applying a vacuum to the wells. By the use of electro-osmosis, groundwater lowering can be extended to coarse silts, but this process is expensive.

563. Present methods of soft-ground tunnel excavation can achieve advance rates from as little as 50 ft/week (hand-mining) to over 300 ft/week (with TBM's). These advance rates should be kept in mind when carrying out a geotechnical investigation for which groundwater control is anticipated. It can take at least a week to install a dewatering control system and an additional week to reduce the piezometric pressures and groundwater flow. Thus the design of the groundwater system must be completed three to four weeks prior to the tunnel excavation operation's reaching the particular section. If the system is underdesigned, tunnel excavation may have to be stopped to avoid burying the TBM due to instability of the face. It is particularly important, therefore, to define the extent of the groundwater problem at an early stage. The cost of groundwater control will generally be based upon an initial installation cost in conjunction with a monthly rental and operating cost. Conditions vary from location to location, so it is not difficult to establish costs on a unit cost basis per foot of tunnel.

Freezing

564. The flow of groundwater in a soil mass can be stopped by freezing the water. It is important to realize that it is the water and not the soil which is frozen.

565. Feeezing is a reliable method of groundwater control but is expensive and slow. Its use is generally limited to small volumes of soil where other methods of groundwater control are not possible, for example, a silt below the water table and near the ground surface. Grouting and pumping are ineffective in fine silts, and compressed air cannot be used too closely to the ground surface or a blowout (loss of pressure) may occur and the tunnel face will collapse.

566. Freezing is carried out by driving pipes into the soil and circulating a refrigerant at a low temperature through the pipes. As with grouting, the operation can be carried out using vertical pipes from the surface or horizontal header pipes driven from the tunnel face. The refrigerant used is usually calcium chloride brine, but quicker results have been obtained with liquid nitrogen. The calculation of pipe size, spacing and time required is a problem in heat flow. The major portion of the heat which must be extracted is the latent heat of freezing of the groundwater.

567. Freezing was used for the construction of a 150-ft long, 6-ft-diam drainage culvert near Abbotsford, British Columbia. The soil consisted of a fine-grained silt with miscellaneous landfill. The water table was about 15 ft below the surface, with severe restrictions on subsidence due to the presence of small structures. Calcium chloride brine was used in vertical 40-ft deep boreholes spaced at 4-ft centers in three rows which were 4 ft apart. The overall cost of the project was $170,000.

568. Ground freezing was used for a small-diameter sewer under Highway 403 near Brantford, England, by freezing from the inside of the tunnel using liquid nitrogen. The use of liquid nitrogen in five header pipes from within the tunnel enabled the freezing to be carried out much faster than with conventional brine, and as there was only a short section of wet silt till, it was not necessary to develop a sequential freezing operation.

569. Ground freezing was used for a 20-ft-diam sewer tunnel project in New York City (Gail, 1972) when unexpected silt and mixed-face conditions were encountered. Freezing was accomplished from the ground surface using

conventional brine pipes at 2.5-ft centers. A long time was required to develop a sufficient thickness of frozen soil so that the excavation could be accomplished. Freezing costs are high, so freezing is used only when other forms of ground stabilization are completely uneconomical or impossible.

Grouting

570. The term "grouting" describes the injection under pressure of a fluid grout, which may be a solution or a particle suspension, to occupy the pores, or the voids in the ground, or between a structure and the ground. Where the ground is water-bearing the grout is designed to expel and to replace the water, or in the absence of water, to fill the voids. When thus injected the grout reacts physically or chemically and may set to form a gel or a solid, reducing the porosity and usually increasing the cohesive strength of the ground, possibly to a very substantial degree. A wide range of materials and grouting techniques and equipment are available to suit particular requirements.

571. The two principal objectives are, as already stated:

a. To reduce the permeability of the ground.

b. To strengthen and stabilize the ground.

Grout types

572. Grouts may be classified very broadly into the following types:

a. Particle suspensions. Portland cement in water is the most familiar; this is only applicable where pore dimensions are sufficiently large to admit the cement particles. Bentonite or other clay suspensions are finer grained and therefore penetrate more freely.

b. Chemical grouts. These are aqueous solutions consisting of pure liquids. Their penetration properties depend on their viscosity, which may increase with time after a physical or chemical action of setting to a gel is initiated. A "one-shot" time-dependent fluid may be used, or a "two-shot" process may be used in which two different materials are injected in succession and react in the ground.

c. Others. These include such grouts as bitumen emulsions and asphalt, which are not often used in tunneling.

573. The choice and design of the most appropriate material and technique and the sequence and pattern of injection can only be made after a comprehensive site investigation with particular emphasis on permeability and sieve analysis. Specialists in grouting are likely to be required for all but

the simplest cases, preferably with an ability to modify their techniques as experience is gained about the response of the particular ground.

Factors influencing the selection of grouting materials and methods

574. The principal factors governing the choice of grout mixtures and methods of application are:

a. Ground characteristics:

  (1) Permeability of the ground.
  (2) Flow of groundwater.
  (3) Groundwater pressure.
  (4) Depth and accessibility of zone to be treated.

b. Grout properties:

  (1) Size of particles in suspension.
  (2) Viscosity.
  (3) Setting time and rate of setting.
  (4) Grouting pressure and injection rate.
  (5) Chemical compatibility.

575. Fissure grouting is aimed at the filling of fissures and joints in rock, and possibly in stiff clay, to reduce the intrusion of water and to minimize movement of blocks disturbed by tunnel excavation. The same principles apply but details of application and technique differ. Grouting of shattered fault zones ahead of excavation may be essential for safe construction. Pilot drilling ahead of the face as far as practicable is required to locate major water-bearing fissures and to allow them to be sealed by grouting. Whatever pattern of drilling is adopted for exploration and for treatment, it is impossible to insure that every fissure and joint is located and treated; a boring may run nearly parallel to the plan of a major fissure and fail to intersect it. Sometimes fissures may be blocked with soft "gouge" which may be washed out by inflowing water when exposed. A useful treatment may be the deliberate washing out of the gouge by high pressure water, followed by refilling with grout.

576. Ordinary portland cement is used to grout gravels and coarse sands, and also in fissure grouting. The average particle size of ordinary commerical portland cement is 30 μm, but individual particles may be up to 100 μm. It is useful where passages for grout flow are of the order of 10 times the particle size.

577. To obtain maximum penetration by the cement, a technique of progressive thickening for successive injections is used. An initial thin mix allows the grout to reach and penetrate and seal finer voids, excess water being expelled into the surrounding ground by maintained pressure. Successive stages with reducing water/cement ratio insure also the filling of the coarser voids. The procedure insures maximum strength and minimum permeability. Initial setting time is about 1 hour, but hardening is a slower process.

578. This progression with a single relatively cheap material contrasts with the technique of initially using cement grout and subsequently infilling the finer zones with expensive low viscosity grouts.

579. Rapid hardening cement is more finely ground and the smaller particle size increases penetration, with the possible added advantage of shorter setting time and high early strength.

580. High alumina cement gives early strength and resists sulphate and acid attack but cannot be used in alkaline conditions. When mixed with ordinary portland cement, there is a very rapid set, useful for plugging leaks or other emergency action.

581. Supersulphated cement is a finely ground mixture produced from granulated blast furnace slag and ordinary portland cement with added calcium sulphate. It has good penetration and is highly resistant to sea water, acids, and sulphates.

582. Other cement-based mixtures may be adopted for special purposes. Addition of sand will provide a cheaper grout for filling large cavities.

583. Other grouting materials have been formulated, namely, cement clay pozzolans and chemical grouts. These are for specialized application.

Application

584. When grouting ahead through the tunnel face, the shape of the treated ground outside the tunnel resembles a diverging cone, formed by the radial fan of grout pipes. The length which can be treated is then limited largely by the accuracy with which pipes can be driven, and also by the angle of divergence of the pipes. A practical maximum length is 15 ft. In special cases a sufficient enlargement of the last length of tunnel will allow a ring of parallel pipes to be driven in a cylindrical pattern.

585. It may not be necessary to treat the whole circumference of the tunnel; a "hood" over the crown of the excavation may be adequate, or other limited arcs where a thin layer of permeable ground intersects the excavation.

586. One major disdvantage of working from the tunnel itself is that ground treatment and tunnel excavation cannot proceed simultaneously, the appropriate plant and the specialized labor for the two operations must alternate, perhaps on a two-week cycle. The tunneling is then slow and costly.

587. Ground treatment in advance from a pilot tunnel has the advantage of continuity of operation and less disruption when the unexpected is encountered. Where a large tunnel is to be built a pilot tunnel may be driven inside its area and may be concentric or at high or low level. Grout pipes are driven out through prepared holes in the pilot tunnel lining and must be more or less radial. This condition imposes two limitations--(a) the length of pipe which can be inserted without a joint, and working space generally, are limited by the diameter of the pilot tunnel; and (b) the radial pattern of pipes means that spacing increases rapidly outward.

588. Ground treatment by grout injection is necessarily a costly operation in which the cost per unit volume of treated grout will vary so widely, even for use of the same grout, as to make comparisons very difficult. The case for using a particular method needs careful study, but use of a grout that fails to affect the requisite reduction in permeability and increase in cohesion is certainly wasteful and may be positively harmful in disrupting the ground.

589. Equipment. The essential plant for ground treatment by grouting includes:

a. Drilling gear.
b. Batching and mixing equipment.
c. Pumps.
d. Grout injection tubes.

590. The operations may range from relatively simple processes, such as cement or bentonite grouting from the surface, to treatment of varied and difficult ground with a succession of specialized grouts, and injections at high pressures from a confined space in a pilot tunnel. In all cases, careful control and accurate records by skilled operators are required, and in more complex applications a site laboratory and expert supervision by specialists are likely to be essential for a satisfactory outcome.

591. Where the surface is accessible, modern drilling equipment will reach any depths likely to be required for tunneling and associated shaft sinking. Grout tubes may be simple open-ended tubes, possibly fitted with an

expendable tip to prevent blockage in driving, or perforated tubes which allow grout to be injected over a length may be used. The "tube-a-manchette" which consists of a perforated pipe and packers, makes possible successive injections of different grouts and choice of the level for injection. Perforations at appropriate intervals are closed by an external elastic sleeve which can be opened by the internal pressure of the grout; the level of injection at any time is regulated by pistons above and below the injection point. Spacing of grout tubes normally is within the 1.5- to 13-ft range, depending on the nature and extent of the required modification of the ground and the permeability and viscosity.

Compressed Air

592. Air pressures above atmospheric pressure are often used for driving soft-ground tunnels below the water table to prevent the movement of water, sand, gravel, and soft materials into the face of the tunnel opening. The design requirement is to develop sufficient air pressure within the tunnel to balance the excess hydrostatic pressures outside. The air pressure required on any project will depend upon the piezometric observations as determined during the actual construction process, guided by the fluctuations recorded at the investigation stage.

593. For any tunnel built under compressed air conditions, a bulkhead and an air lock must be installed to retain air. The air lock consists of a chamber with an airtight door at each end, the doors being arranged so that only one door can be opened at any one time. Pressure within the air lock is regulated so as to be equal to the pressure on the other side of the first door to be opened, and then after closing the door the air pressure is increased or decreased so as to be equal to the pressure in the second part of the tunnel. On larger tunnels, there will be separate air locks for men and materialhandling to minimize the volume of air that must be regulated. In some cases, an emergency air lock may also be installed.

594. The presence of the air lock has a substantial effect upon the tunnel construction costs in at least three ways:

a. Because of health regulations, the amount of time that the labor force may operate under compressed air is limited, and productivity of the labor force is lower. Usually, bonus pay will be required and decompression time must also be included in labor rates.

b. There is an increased complexity introduced into the shifts for men and materials-handling cycle. Each cycle in the materials-handling sequence will be lengthened.

c. There is a high initial cost of the installation of the air lock, combined with a continuing maintenance cost of equipment, additional labor, and supervision.

595. The reduction in the length of working shift along with the increasing amount of decompression time where the air pressure exceeds 14 psi over atmospheric is substantial, and for this reason, every effort should be made to keep the pressure below this figure.

Groundwater Control in Shafts

596. Groundwater can have a major effect on the cost of shaft excavation. Groundwater is unpredictable because it varies with the season and with the elapsed time after the excavation has been made, varying from no water to thousands of gallons per minute. Even though the presence of groundwater can be predicted through core samples and packer tests, it cannot be completely stopped by pregrouting. Groundwater investigations done in the fall will not identify water that could appear in the spring. Postgrouting to stop water flowing into the shaft is difficult, and can be impossible if the flow is very large. Water can add to the slacking of the sidewall, interfere with the mucking system, endanger the workers, require special water clarification systems when pumping from depths over about 250 feet, and increase the maintenance on mechanical systems. Water is present in nearly all underground workings to some degree, and usually leaks through the shaft wall at cold joints. Water seeping through the shaft wall can freeze in downcast ventilation shafts during the winter months, forming large ice deposits attached to the shaft wall. When the air warms, melting ice falling from the sides can close the shaft to personnel. The disposal of groundwater can have environmental implications because it may contain acids, alkalines, or may have other unacceptable properties.

597. The design of the lining is influenced by groundwater because water is usually present to some extent in all shafts. Even small quantities can build full pressure heads against the walls. Good design practice is to assume a full hydrostatic head acting on the lining. Grouting between the shaft wall and the rock (back-wall grouting) seals out the water.

Tubes, corrugated metal, and rubber matting are all used to provide space for routing the water to water rings, shown in Figure 62, or to the bottom of the so that high pressures will not occur. If care is not taken, silt or chemical deposits can eventually plug escape routes, but the increased pressures usually force the water into other escape routes. Water escape routes are almost always used behind concrete liners. A thick steel liner is the only liner that is assured of withstanding hydrostatic pressure below about 600 ft without leaking. Groundwater handling techniques peculiar to specific excavation techniques are discussed in the respective sections in Part III.

PART VII: AUXILIARY OPERATIONS

Ventilation

598. Forced ventilation is required to remove gases, fumes, heat, and dust from working areas. It impacts upon the safety and health of workmen and efficiency of equipment. Although ventilation for civil engineering tunnel construction is of critical importance, the subject has received little attention in published literature. However, much well-documented literature exists on ventilation for mining operations; this is especially true for coal mining where ventilation requirements are most stringent. The equipment and methods used in mine ventilation are applicable to civil engineering tunneling excavation but are generally more developed than that required for most such projects. Factors to be considered in the design of a ventilation system for tunnel excavation include the following:

- a. Length of tunnel.
- b. Cross-sectional area of tunnel.
- c. Size and location of shafts.
- d. Whether equipment will be electric or diesel powered.
- e. Heat generated by men and equipment.
- f. Ambient temperature of the ground.
- g. Fumes produced by equipment and materials (blasting, shotcreting).
- h. Dust produced by the excavation process.
- i. Likelihood of natural gases.

599. The usual approach in most mine ventilation systems is to use portals and access shafts for personnel and equipment as inlet and exhaust openings for air. In tunneling, previously excavated pilot and service tunnels may be used to provide supply or return air for the main tunnel during its excavation. In addition to fans at inlet and exhaust openings, the need sometimes exists to place fans at intervals to move the air through an underground system.

600. Ducting is a necessary means of ventilation for a drive ending in a blind heading, which is a usual tunneling situation. Pressure systems deliver fresh air to the face; and vacuum systems remove contaminated air from the face. Both are used, and combined or alternating systems are also used;

most ventilation systems are reversible which facilitates control of fire or by-products of explosion. For example, a vacuum system at a face would quickly be reversed in the case of fire in the tunnel so that fumes and heat from the fire would not be drawn toward the men and equipment at the face. The most suitable operating mode depends upon the project as a whole, although most are vacuum systems. If the face is the only work area, a direct supply of fresh air may be advantageous from the standpoint of making the area habitable as soon as possible after blasting (Megaw and Bartlett, 1981), and such a pressure system precludes the possibility of fumes, gases, or dust being drawn from other parts of the tunnel. However, if work on supports or lining is in progress, the blowing back after firing at regular intervals of a cloud of fumes and dust would be unacceptable and make a vacuum system at the face preferable. Although the entire ventilation system may be ducted, a mixed system of air circulation through a mine or tunnel system and forced air ducting where blind headings exist is less costly than ducting all ventilation. Ducted ventilation to a heading should be reversible and should terminate about 100 ft from the face (Mayo, Adair and Jenny, 1968). Exhaust from the working face should continue for 20 min after firing. This will remove most of the explosives, fumes, and fine silicates.

601. In recent years great progress has been made not only to improve air conditions underground, but also to reduce power costs and to lower noise levels associated with ventilation systems. This has come about with the advent of in-line blade-type blowers (fans) in a ducted straight exhaust system (Philpott, 1981). The system starts with a suitable blower at the portal to ventilate, for example, 2000 linear ft of tunnel. Similar blowers are installed to take care of each additional 2000 ft. The system should have a rock trap and nose screen at the heading end of the pipe. Reversible starters can be specified for certain emergency situations and explosion-proof motors and starters are used where gaseous conditions may be encountered.

602. Duct sizes typically range from 2 to 3 ft in diameter and even larger sizes may be required where extensive use is made of diesel-powered equipment. A fan line is commonly the same diameter throughout. However, should a situation arise where more clearance is needed for equipment away from the face, a smaller diameter could be used to move the same quantity of air at a higher velocity. Additional booster fans would be required.

603. Duct diameter and fan brake horsepower (BHP) based on required cubic feet per minute (cfm) were given by Parker (1970). In one application, a 14-ft-diam horseshoe tunnel driven with battery and air-operated equipment, and requiring 50 cfm per square foot of tunnel face, required the use of a 24-in.-diam duct, a 40 BHP fan at the portal, a spacing of 3000 linear ft to the second fan, and a spacing of 3240 linear ft for each additional fan required. In another application, three 109 BHP dumptors and one 143 BHP overshoot loader were used; ventilation required (based on 75 cfm per BHP) the use of a 38-in.-diam duct, a 100 BHP fan at the portal, a spacing of 1520 linear ft to the second fan, and a spacing of 2000 linear ft for each additional fan required. In six underground coal mines operated by Jim Walter Resources, Inc., in Alabama, face ventilation is an exhaust system using 50 BHP auxiliary fans with 30-in.-diam rigid fiberglass tubing, while primary mine fan requirements vary from 200 to 3500 hp (Stevenson, 1981).

604. Size of components required to obtain a given air volume were given by Parker (1970) as tabulated below:

Air Volume cfm	Pipe Size in.	Fan bhp	Fan Nominal bhp	Maximum Spacing, ft	
				First Fan	Others
80,000	48	117	125	120	720
75,000	48	120	125	320	960
70,000	48	95	125	320	960
65,000	48	100	125	640	1,280
60,000	48	100	100	520	1,120
55,000	45	90	100	720	1,320
50,000	42	75	75	440	960
45,000	42	120	125	1,720	2,240
40,000	42	100	100	2,120	2,680
37,500	38	106	125	1,240	1,680
35,000	38	90	100	1,520	2,000
30,000	38	86	100	2,560	3,000
27,500	36	92	100	2,040	2,480
25,000	36	75	75	2,640	3,080
22,500	34	48	50	1,800	2,200
20,000	32	45	50	1,440	1,800
17,500	32	38	40	1,940	2,300
15,000	30	30	30	1,760	2,080
12,500	26	29	30	1,520	1,800
10,000	24	40	40	3,000	3,240
7,500	24	28	30	4,960	5,200
5,000	18	18	20	1,920	2,120
4,000	18	15	15	3,040	3,240
3,000	18	10	10	4,320	4,480

Required fan BHP decreases with increase in elevation; for example, at 5000 ft a reduction to 84.5 percent of that required at sea level would be made.

605. Several types of ducting may be used depending upon ventilation requirements and overall size of the tunneling project. Collapsible plastic tubing may be used on short tunnels where capital cost is a large factor in total cost; with this tubing, ventilation must be a pressure system blowing air into the tunnel. For most applications rigid pipe is used and may be fiberglass, plastic, or steel.

606. A money-saving innovation has been the fabrication of ventilation pipe on the jobsite (Philpott, 1981, and Parker, 1970). This saves the expensive transportation cost of prefabricated pipe; because of the volume to be handled, such transportation cost can be more per foot of finished pipe than the total cost of pipe fabricated on the site. Also, the smaller volume prior to fabrication would allow for convenient storage. Coils of steel strip are delivered to the jobsite from which special machines make spiral-rolled pipe of various diameters. The finished sections of pipe join with airtight clamping rings for quick connections. Tests have shown that pipe rolled on the job with a groove every 3 in. actually has a lower coefficient of friction than smooth pipe; and at the same time the grooving imparts to lightweight pipe the stiffness of material 2 to 4 gauges higher. Pipe of this design used for transporting wood chips (via air) in lumbermills has a very long life; the vortex effect of the spiraling of the air-wood chip mixture on the inside of the pipe reduces the abrasive action of the chips.

607. Ventilation in vertical and inclined shafts is essential for safe shaft operation. Common ventilation methods on United States shaft projects use a 40- to 100-hp electric fan with 24- to 36-in.-diam vent tubing (Dames and Moore, 1977). The fan is offset at least 15 ft from the shaft collar as prescribed by law and is connected to 24- to 36-in.-diam steel or fiberglass ventilation tubing. The fans are reversible and may be set to blow air into the shaft or exhaust air from the shaft. Most commonly, the fan blows air into the shaft through the tubing with the air being returned up the shaft.

Hazards

608. Elimination or minimization of hazards in the tunnel or shaft during construction involves ground support, groundwater control, and

ventilation which are discussed elsewhere in this report. Also, all safety regulations must be followed.

609. In addition to the well-regulated and relatively straightforward considerations of sanitation, first aid, proper lighting, protection of personnel from high voltages, the safe use of machinery and equipment, and the use of personal protective items such as hard hats and hearing protection, the tunneling environment is such that special attention in planning of the work, selection of equipment and monitoring of potential hazards must be given to dust, noise, heat, radiation, natural gases and gases introduced by tunneling operations.

Dust

610. Dust can be generated by all excavation methods although drill and blast operations produce large quantities of fumes and dust. When tunneling through rocks of the silicate family, adequate (high-volume) ventilation is a must (Mayo, Adair, and Jenny, 1968); in addition other dust-control methods may be employed. Silicosis, or miners' asthma, is a lung disease which can affect men working in such an environment. Tunnel boring machines frequently employ water spray at the face for effective control of dust. Whatever the method of excavation, muck piles should be wetted to minimize dust before the muck is loaded or transported.

611. Airborne dust is primarily controlled by ventilation; however, other methods are employed such as the use of pressure spray foam which produces minute bubbles 0.004 to 0.008 in. that collapse around and wet dust particles which adhere to each other causing their fallout. Such a system is marketed by Deter Company, Inc., East Hanover, N. J. Circulating filters operating near the source and personal respirators may also be employed where the ventilation alone does not adequately eliminate dust.

612. While dust is visible, monitoring equipment is commonly used; mechanical and electronic filtration are used to trap and measure dust quantity and size. Dust detection lamps are available to allow a visual or photographic check for dust which may be invisible to the unaided eye.

Noise

613. Even though equipment manufacturers continue to make progress in noise reduction, noise levels associated with excavation and mucking operations are high and are produced within the confines of ground having poor sound-absorbing characteristics. Noise levels are frequently high enough that

personal hearing protection is required. U. S. Army Corps of Engineer Manual 385-1-1 (1 March 1967) requires personal hearing protection for levels above 85 decibels.

614. Tests have shown that pneumatic rock drills are the noisiest equipment used (Djamgouz and Lewis, 1974), and several techniques have been used to reduce their noise level. Drilling with water has been shown to dampen the source of noise. Reflected rock drill noise can be significantly reduced by application of an aqueous foam applied to the rock surfaces of an underground opening. Effects of this foam are greatest in the higher frequency range (above 1000 Hz), and the noise reduction efficiency increases at increasing distances from the drill.

615. The Bureau of Mines has developed and field-tested a compact exhaust air muffler for mechanized, jumbo-mounted pneumatic rock drills (Visnapuu et al., 1979). Field tests in actual mining operations showed a 15 db reduction in exhaust noise and an 8 to 12 db reduction in overall drilling noise. The system has no icing problems and does not decrease drill performance.

616. Hydraulic rock drills have come into wider use in recent years; one of the benefits realized by the use of these drills is a better working environment due to the absence of oil-water mist fogging and a reduction in noise levels as compared to pneumatic drills (Martin, 1979). Although there is a noise reduction with the use of hydraulic drills, there is a greater chance of damage to the unprotected ear because of the higher frequency (Weakly, 1979). The hydraulics produce 3000 to 8000 Hz as compared to 100 to 1000 Hz generated by pneumatic drills. Assuming hearing protection is worn, there is an approximate 40 percent increase in sound attenuating efficiency at the hydraulic drill frequencies; in such a case, there is not only a lower noise level but the noise is more attenuated by personal hearing protectors. Even with hydraulic drills, hearing protection must still be worn close to the drill; several manufacturers list operating sound levels above 100 db at the console.

Heat and radiation

617. Heat produced by tunneling operations can usually be adequately handled by ventilation. However, more stringent ventilation requirements and/or a need for artificial cooling exists where virgin rock temperatures are high, as in the case of very deep sites or in areas of high thermal gradient

(Graham, 1976). Natural rock may also be radioactive, and in such case careful monitoring of exposure by personal radiation badges is necessary. Radiation may be taken into the lungs if the gaseous element radon is present or if radiation exists as part of airborne dust. This problem is rare in the tunneling environment; where it exists the radiation can be diluted by increased ventilation and the effects on personnel minimized by limiting exposure hours.

Gases

618. Gases in tunneling are hazardous because of their explosive, toxic, and oxygen-displacing properties. The primary means of control of gases is ventilation. Steps should be taken to improve ventilation if a gas reaches 40 percent of the specified maximum (Mayo, Adair, and Jenny, 1968). This usually means increasing ventilation volume; if the source is localized, relocating the vent on the fan line may adequately bring down the concentration without an increase in volume. In rock tunnels it is often possible to locate the fissure or seam from which a gas is flowing, and seal the source with grout.

619. Monitoring of airflow and gas concentrations is necessary for the control of gases. The monitoring of methane and airflow has been practiced for many years in underground mining operations. In recent years many measurements of environmental quality underground have been required (Murphy, Bowser, and Scott, 1979). The vast majority of these measurements are made by personnel on a cyclic basis. However, monitoring from a central location has been successfully accomplished at some mining operations; such monitoring systems consist of sensors, telemetry links, displays, alarms, and perhaps analytical capability. Such systems provide for continuous monitoring, even in unoccupied areas of the mine. Also, tube bundle systems have been used for monitoring in mines from a central location either on the surface or underground; samples travel through small diameter tubes from diverse locations to a central analysis unit. The major drawback to the use of such systems is long sample transit times (sometimes as much as several hours) for applications where early warning is essential.

620. Gases commonly monitored are methane, carbon monoxide, and oxides of nitrogen. Other gases may be present in the tunnel environment. Hydrogen sulfide, a product of organic decay, can be highly toxic (Megaw and Bartlett, 1981); it may be present in existing or abandoned sewers and can migrate to adjacent new underground construction. Sulfur dioxide is toxic; it results

from combustion of sulfur and its compounds, and it may appear naturally in volcanic areas.

621. Carbon dioxide is not toxic but can be dangerous by displacing air. It is heavier than air and tends to accumulate in pits, sumps, and at the lower end of tunnel drives. It is produced by complete combustion in coal or other fires, by acid acting on limestone, and by diesel exhaust. It is not directly monitored, but its effects of reducing the oxygen present in the air may be sensed by use of an oxygen analyzer.

622. Methane originates in strata having organic content and may migrate through fissures into adjoining areas. It is common in the vicinity of coal deposits but may also be associated with decaying vegetation in lake beds, peaty deposits, or even rubbish dumps. It is lighter than air and is easily ignited at concentrations of 5 percent or more with a resulting explosion (Megaw and Bartlett, 1981). The majority of methane detectors used underground use a heat of oxidation-type sensor (Murphy, Bowser, and Scott, 1979). Long-term stability of such devices has been attained by recent improvements in the quality of the device and associated electronics design. Catalytic methane detectors are being used for long-term monitoring of return airways and exhaust fans with success.

623. Carbon monoxide and oxides of nitrogen are produced by diesel equipment. Also, oxides of nitrogen are in blasting fumes, and carbon monoxide may be produced by any underground fire where combustion is incomplete. Electrochemical sensors appear generally more suitable than other sensors for monitoring of carbon monoxide in underground applications (Murphy, Bowser, and Scott, 1979). Such sensors were in use in 1979 as prototype devices for monitoring oxides of nitrogen.

624. As stated previously, diesel exhaust produces large volumes of carbon monoxide, carbon dioxide, oxides of nitrogen, particles and heat. Parker (1970) cited state requirements for diesel horsepower for ventilation to range from 50 to 100 cfm. These requirements make necessary very large (sometimes multiple) ventilation ducts with accompanying high fan horsepowers. These extreme ventilation requirements have been reduced by the use of oxy-catalytic exhaust scrubbers which eliminate most of the toxic gases in diesel exhaust (Hews and Rutherford, 1975). Control of other factors--the choice of clean-burning diesel engines using preminum grade fuel to minimize toxic fumes produced, proper maintenance of engines which require a high degree of skill

and effective maintenance training programs (Stefanko and Ramani, 1975), and frequent monitoring of atmospheric conditions at the source--also reduces ventilation requirements where diesels are used. The Bureau of Mines has developed a diesel exhaust particle filter for underground use (Freedman, Duerr, and Litton, 1979); removal efficiencies of close to 90 percent have been reported with variations in engine load having little effect on collection efficiency.

625. Control of all gas hazards is dependent on control and maintenance of ventilating volume; blockages or leaks in the ventilating system should be sensed early, before gas concentrations build up. Numerous types of transducers have been tried to monitor airflow. Hot wire anemometers and rotating vane anemometers tend to be fragile and/or are rapidly affected by accumulation of dust or moisture (Murphy, Bowser, and Scott, 1979). A vortex-shedding anemometer, produced by J-Tec of Cedar Rapids, Iowa, has been used for several years under ground and is not affected by dust or moisture. An alternative method of monitoring airflow is to read differential pressure between intake and return airways.

Fire

626. Sources of combustible or explosive materials in underground excavations include flammable ground; airborne dust produced in excavation of such ground; methane; the higher hydrocarbons which are likely to be found when petroleum products, either natural or man-made, are encountered (Thomas, 1974); and combustibles brought in, such as wood and plastics. Ignition sources for underground fires include electrical spark, mechanically produced sparks, friction of cutting or drilling, and equipment fires usually resulting from poorly maintained equipment. If the possibility of an explosive atmosphere exists, these ignition sources must be made ineffective by close monitoring and adequate ventilation. Also, precautions must be taken to eliminate the sources of ignition; particularly, all electrical equipment must be of explosion-proof construction (Lee, Marshall, and Silver, 1975).

627. When fire is present, its detection in the early stages of development is accomplished by monitoring temperature (Murphy, Bowser, and Scott, 1979). With the introduction of suitable carbon monoxide and submicron particle sensors, earlier warning is possible; these sensors are particularly more effective for smoldering fires.

628. A fire may be controlled by use of fire suppressants such as water, dry chemical types, carbon dioxide, fire fighting foam, and halogenated agents (Pomroy, 1977). A fire may also be controlled by manipulation of the ventilation system. A fire control system should be designed such that it can be quickly cut off by closing vents, thereby eliminating part of the oxygen supply to the fire. These systems should also be reversible, both for control of the fire, if needed, and to control by-products of fire or explosion so that fumes and heat are drawn away from men working in the tunnel.

Health and Safety Considerations in Shafts

629. During shaft sinking, miners are exposed to many health and safety hazards. To safeguard these workers, the Code of Federal Regulations (CFR) contains hoisting standards that apply to those hoists and appurtenances used for hoisting persons. However, where persons may be endangered by hoists used solely for handling ore, rock, and materials, other appropriate standards should be applied.

630. Adhering to CFR standards will improve working conditions, but many hazardous conditions exist that are not covered by the CFR; therefore, effort must be directed toward providing worker safety and health above CFR requirements, as each shaft is unique and has its own set of personnel health and safety hazards.

631. Man hoisting in metal and nonmetallic underground mines is covered in Section 30, CFR 57.19. Mandatory standards are given for hoists, wire ropes, headframes, sheaves, conveyances, hoisting procedures, signaling, shafts, inspection, and maintenance.

632. Worker exposure to airborne contaminants shall be within threshold limits in the publications entitled, "TLV's - Threshold Limit Values for Chemical Substances in Workroom Air Adopted by ACGIH for 1973," as referenced in 30 CFR 57.51, and "TLV's - Threshold Limit Values for Substances in Workroom Air Adopted by ACGIH for 1972," as referenced in 30 CFR 75.3012.

633. Ventilation standards are numerous and rightly so as ventilation air is necessary for controlling gas concentrations, airborne contaminants, oxygen concentration, radioactive atmospheres, air temperature, and many other air quality variables.

634. Long-term health and safety of workers is also dependent on exposure to dust, noise level, illumination, and machinery used in the workplace.

635. The proper choice of shaft sinking equipment and its design can reduce hazard exposure to workers. Recent safety analyses conducted by Battelle's Pacific Northwest Laboratory, under contract to the Bureau of Mines, show that the potential risks to workers from conventional shaft sinking could be reduced 30 percent by using a blind-shaft borer, or could be reduced 35 percent by using the impactor shaft sinking system.

636. Current trends are for shafts to be circular and concrete lined. At higher construction rates, accelerators are used to shorten concrete set time; however, these products are caustic and chemical burns may result.

637. Health and safety considerations need to combine conformance to CFR standards, selection of sinking method that has low risk potential, worker training, and effort to keep the workplace in a safe condition.

638. All references made to the Code of Federal Regulations are contained in one volume, "CFR Title 30-Mineral Resources," Parts 0-199. Sales are handled exclusively by the Superintendent of Documents, Government Printing Office, Washington, D. C. 20402. Copies of material incorporated in the CFR, such as the TLV's, are available at MSHA district and subdistrict offices. These materials and listings of addresses are included at the end of the CFR volume.

Regulations for Safety and Health

639. In tunneling, consideration of safety and health are critical in nearly every step of the work. Compliance with applicable guidelines is essential and usually required by law. A hazard analysis by phase of construction is required in the planning and design phases by Corps of Engineer Manual EM 1110-2-2901 (U. S. Army Corps of Engineers, 1978). This is required even though the construction contractor will be responsible for compliance with pertinent safety regulations. The following are applicable to tunnel construction:

a. U. S. Army Corps of Engineers. 1 Mar 67 with Change 1, 27 Mar 72. "General Safety Requirements," Engineer Manual 385-1-1.

b. U. S. Bureau of Reclamation, Division of Safety. 1971. "Safety and Health Regulations for Construction."

_c_. U. S. Bureau of Mines. 1968. "Tunneling: Recommended Safety Rules," Bulletin 644 (Revision of Bulletin 439).

_d_. Department of the Treasury, Bureau of Alcohol, Tobacco, and Firearms. 1970. Publication No. 7550.3 (Revised 5-74), "Title XI, Regulation of Explosives," (Public Law 91-452, Organized Crime Control Act of 1970).

_e_. Department of the Treasury, Bureau of Alcohol, Tobacco, and Firearms. 1977. Publication No. 7550.4, "Commerce in Explosives," (Part 181 of Title 27 Code of Federal Regulations).

_f_. State Safety Regulations, in the state where work is to be performed.

Instrumentation and Monitoring

640. Instrumentation during construction is needed to monitor tunnel stability and to determine whether the support system and the rock mass behave in accordance with design assumptions. This instrumentation is closely related to, and should be coordinated with, instrumentation used before construction for determining information required for the design of the excavation; such information may include the state of stress, modulus of elasticity, and strength of the in situ rock. After construction, instrumentation is required to monitor long-term stability and the response of tunnel rock mass and supports to imposed loads; some of this instrumentation is installed and used during construction and left in place.

Detection of unstable conditions

641. The most usual, and probably the best, method for detecting unstable conditions is by measurement of convergence of the rock surfaces within the tunnel. Tape or rod extensometers for measurement of convergence, as well as borehole extensometers, offer excellent long-term instrument stability (Hoek and Brown, 1980). Strain measurements on various types of rock bolts, steel sets, or other support as well as stress measurements within the rock are considered less reliable indicators of instability because of the influence of local conditions at the point of measurement.

642. Convergence measurements across tunnel diameters or across various chords of noncircular excavations are commonly made using a tape extensometer. Periodic measurements are made between pins set in the rock, or heads of bolts may be used. The spring-loaded tape is stretched between points and the reading taken from a dial gage or suitable electronic transducer. Tube or rod

extensometers are also available which give very good results for vertical measurements (Corps of Engineer Manual 1110-2-2901, 1978, p. 5-4). However, where horizontal distances are greater than 8 ft, the results are less reliable. A variety of extensometers are commercially available. Convergence measurements may also be taken using electronic distance measuring instruments; a target can be installed on the crown or elsewhere and periodic measurements conveniently taken even in a large excavation where the target is not readily accessible.

643. Borehole extensometers are used to measure displacements in the rock mass adjacent to the surface of an underground excavation. A simple borehole extensometer (the single-point rod type) consists of a stiff rod anchored at the bottom of a drill hole with its free end encased in a collar anchor at the surface of the hole (U. S. Army Engineer Waterways Experiment Station, 1980). Measurements are made between the fixed collar anchor and the free end of the rod; a dial gage or electrical transducer may be used. This type extensometer has the disadvantages that the depth would normally be limited to one tunnel diameter because of the stiff rod, and that deflection is sensed only between the tunnel surface and the end of the rod so that no interpretation can be made as to whether the movement is superficial or deep-seated. However, multipoint rod extensometers have been developed that require only one drill hole, and multiwire extensometers are available that are capable of measurements to depth of 1000 ft; with multiple anchor points, displacements can be measured relative to various depths. Up to six anchor points are available in rod extensometers and up to eight in wire extensometers (Hoek and Brown, 1980).

Determination of support system performance

644. The primary measuring devices used to measure loads on support or the effect of such loads are load cells and strain gages. A load cell is a deformable member which can be positioned to carry the load where it is transferred to a support or to carry the load where elements of a support structure react against each other. The deformation of the load cell can be converted to a corresponding load using the modulus of elasticity of the cell's material and its geometry. Load cells are calibrated prior to use by imposing known loads and observing readings of the transducer used to indicate strain.

645. Strain gages are devices used to measure linear deformation, over a given gage length, occurring in the material of a structural element during loading. Strain gages are used as the means of deformation measurements in some types of load cells as discussed below; however, they may also be installed directly on the surface of the support. Once strains are measured, stresses and forces in the support member may be computed. Although other types have been used, the bonded variable resistance wire strain gages are very useful for this purpose because they are stable over long periods, reasonably easy to install, flat and small in size, and can be left in place after initial use so that associated electronic instrumentation can be reconnected for future readings; however, they cannot be reused. This resistance strain gage consists of multiple lengths of conducting material electrically in series and mounted parallel to each other on a backing material. The backing is glued to the structural element to be tested, and the gage is overcoated in place with special material to protect against moisture or mechanical damage. The resistance of the gage varies as the conducting element is deformed by strain changes in the structure. The change in electrical resistance from one reading to another is a measure of the change in strain which corresponds to a given stress change for a particular material. Multigrid gages are available which can measure strains in several different directions at the same point of application.

646. Load cells can be placed between the support and the rock to determine loads on the support. When placed between steel sets or concrete and the rock, several such instruments should be installed to obtain a representative sampling of actual conditions. They may also be placed in the structural system. This is commonly done with steel arch support sets. Measurements of compressive loads actually being supported by the arch provide a direct means of comparing actual loads with assumed support design loads; a decision can then be made as to whether to change the steel set spacing. However, measurements on many steel sets would be required to determine the range and expected maximum applied loads before changing design of the support. Load cells are generally installed under the baseplates of steel arch sets; however, it is sometimes desirable to include a crown load cell, and in squeezing or swelling ground, load cells may be placed in invert struts to measure side loads. In these cases, they are placed at the time of set placement, the sets being altered to accommodate them. Provisions can be made for

removal of the load cells after a particular section of the tunnel has stabilized, allowing the load cells to be reused in leap-frog fashion at a considerable cost savings. Actual loads acting on rock bolts can be monitored by placing a hollow core load cell between the bearing plate and the nut or other tensioning device. After tunnel stabilization, the load cells can be removed one at a time and reused as the tunnel advances. Calibrated torque wrenches have been used to apply a specified tension during rock bolt installation or to estimate loss of tension in a previously installed bolt (U. S. Army Engineer Waterways Experiment Station, 1980). However, tests have proven that such torque measurements can produce errors in bolt tension as much as one or two times the indicated load. Therefore, the load cells are preferred for accuracy.

647. Load cells have been developed using a number of different physical principles in a variety of designs. The strain-gaged load cell is the most commonly used in both field and laboratory applications. These load cells are usually constructed by use of a hollow metal cylindrical column which is loaded axially, and the axial strain is measured with a strain gage, which can be mounted inside for protection. Most manufacturers use the bonded variable resistance wire strain gages described above because of their simplicity and availability. Load cells using this type of strain gage are relatively small for their load capacity, can be read directly without summing and averaging or using correction factors to obtain true readings, and have good temperature stability over wide temperature ranges. They have the disadvantages that extreme care is required in waterproofing to prevent electrical leakage and in the bonding technique required to assure long-term stability of the cell; also, recalibration is required when changing cable lengths.

648. Load cells using unbonded variable resistance strain gages have not been widely used. They work on the same principle as the bonded type except that each conductor is mounted at the ends only; the same type equipment is used to take readings.

649. The vibrating wire load cell uses several wires mounted to the cylinder at their ends. As the cell is subjected to load the strain in the cylinder body reduces the tension on the wire, changing its frequency. Wires in different positions around the cylinder are read separately and the readings averaged, which reduces errors caused by eccentric loading of the cell. The advantage of this type load cell is that loads are read as a frequency,

reducing problems caused by changes in resistance of cables. Long signal cables may be used up to the point that the signal is attenuated beyond the sensitivity of readout equipment. Disadvantages of the vibrating wire type load cell are their physical size, cost of manufacture, poor temperature stability, expensive and complex readout equipment, and vulnerability to shock damage.

650. Hydraulic load cells consist of a fluid-filled deformable chamber connected to a pressure gage or an electronic pressure transducer. The load is transferred to the fluid by a piston or by deformation of the fluid confinement chamber as in the case of a flatjack (a fluid-filled chamber between two steel plates welded at the edges). Although this type load cell is generally of rugged construction, their application is limited due to their physical size, poor load resolution, and poor thermal stability.

651. Mechanical load cells consist of an elastic disk or spring between two plates. The elastic element deflects under load, and the deflection is measured with a dial gage or an electronic transducer. The chief advantage of this cell is that it is relatively inexpensive to manufacture but it exhibits a nonlinear calibration curve.

652. Photoelastic load cells consist of a cylindrical steel column with a hole through its center; birefringent material is locked in place in the hole. When polarized light passes through this material, fringes can be observed when viewed through a polarizing filter. The cell is calibrated or read by counting the interference fringes produced by a given load. This type of load cell is rugged and comparatively simple; however, its use is limited because of its coarse calibration and because it cannot be read from a remote location.

Alignment and Grade Control

653. Alignment and grade of a tunnel at the face must be continually checked during excavation. Generally, specialized surveying equipment for tunneling is not needed; high-order, surface-type techniques are used, with many surveyors being competent to carry out the required measurements. The advent of lasers and associated electronics has made this job easier. Laser systems can be explosion-proof for use in a methane atmosphere (Van Suilichem, 1979). A precision beam deflector (PBD) has been developed specifically for

use in underground work (Marshall, 1981). The PBD uses a pair of matched optical prisms which are adjustable to redirect a laser beam when it is being used for guidance during tunnel drives. The PBD eliminates the time-consuming process of repositioning of the laser at chord points and allows location of the primary instrument at a site away from the hazards of the work zone. Lasers have been used for guidance of tunnel boring machines. Alignment and grade can be adjusted continuously by use of targets located on the machine, an instrument located a convenient distance back in the tunnel, and feedback either to the operator or directly to the steering control mechanisms of the machine.

PART VIII: CONCLUSIONS AND RECOMMENDATIONS

654. During this study, an extensive literature review was conducted, tunnel equipment manufacturers were interviewed, and recognized tunnel experts were consulted. Much data were collected. However, detailed information could not be obtained in a few areas and time did not permit in-depth analysis of some collected data. Continued data collection and analysis could significantly enhance and broaden the depth of coverage of selected subject areas, for example, tunnel costs.

655. In the preceding parts of this report, tunnel and shaft excavation methods; muck handling systems; support and lining; ground stabilization; groundwater control; and auxiliary operations, including ventilation, hazards, health and safety considerations and regulations, instrumentation and monitoring, and alignment and grade control, have all been separately discussed. However, all of these operations and considerations must be integrated and balanced to produce an efficient construction program. This integration of operations is required even for very small projects and is absolutely essential for large projects, such as the proposed deep basing concept.

656. To properly accomplish this task, detailed information must be known about tunnel and shaft sizes, depths, layout, lengths, end uses, and site geographical and geological characteristics. Geological conditions are seldom understood in sufficient detail, but the layout, size, shape, end uses, and topography are known in advance.

657. This type of detailed information is not yet available for the deep basing concept. System layout, size, shape, and depth, and site conditions are unknown. Preliminary concepts have been developed (TRW, 1982) and desirable site characteristics and potential sites are being studied, but no final decisions have been made on deployment configurations or siting. These issues will be the subject of further study and refinement.

658. Enough preliminary information is known, however, to provide a general assessment of the feasibility of DB construction. The general assumptions for this assessment are that an immense complex of tunnels, caverns, and shafts would be constructed at depths of approximately 2,600 ft. Precedents for the construction of shafts and tunnels and mines at this depth, and even deeper, exist in the world tunneling and mining community. Some of these have been cited by Mathews (1977) and include shafts and mines at depths of 5,000

to 7,000 ft in the United States, Canada, and South America, and shafts and gold mines operating at 10,000-ft depths in South Africa. Similarly, several very long (25 to 50 miles long) tunnels and very large caverns in rock have been constructed.

659. Likewise, civil engineering projects of immense dollar value have been successfully completed, e.g., the Alaska Pipeline, the WMATA and MARTA, BART, and other rapid transit systems. So the DB concept is not without precedent in size, complexity, or cost.

660. With the above considerations in mind, some conclusions can be drawn about the feasibility and constructibility of the proposed DB facility.

661. Methods exist for construction of the required lengths of tunnels and shafts to the depths referenced. Such construction can be accomplished under nearly any conceivable underground conditions. (The experience of the Japanese tunnelers on the Seikan Tunnel attest to the fact that tunnels can be constructed under very difficult conditions.) Certainly, the idea here, though, is to find the right combination of site characteristics, construction methods, and design requirements to meet the objectives of a DB facility that can perform its required mission in as timely and economical a manner as possible. It is believed that this goal can be accomplished using proven technology.

662. Tunnel boring machines are ideally suited for excavation of tunnels through uniform soft to moderately hard rock, and recent experiences in hard rock and variable ground have been encouraging. TBM's may be used to bore horizontal, upgrade, or downgrade tunnels, and experimental machines have been developed for boring blind shafts.

663. Often TBM's have successfully bored through short zones of very hard rock or blocky ground or water-bearing zones. However, progress is usually quite slow. If the entire tunnel alignment was in such unfavorable rock, the method would probably be uneconomical. Much longer segments in favorable rock conditions allow time lost in these bad zones to be made up and allow a satisfactory overall advance rate to be achieved.

664. In the very long tunnels envisioned for DB, careful planning and site investigation can be used to select alignments through favorable rock conditions. However, because of the immense size of this proposed facility, it is inconceivable that a site could be found where all tunnels would be constructed under the stated desirable conditions. Indeed, water-bearing

zones, crushed or shattered rock zones, squeezing or swelling rock, and faults are almost certain to be encountered to some extent. A well planned and executed site investigation program can help predict the frequency of occurrence of these conditions, and in some cases, the alignment may be altered to avoid poor ground zones. However, control measures should be planned in advance and the necessary equipment and personnel should be provided to deal with these critical zones as they occur to avoid unnecessary delays and costs. Examples include provisions for grouting ahead of the face and installing support very near the face. Provisions should also be made for maintaining face stability by using TBM design features described in this report. This approach will result in a versatile TBM that would be able to bore through variable ground with steady, predictable progress. Such a machine would cost more than a standard design.

665. Drill and blast excavation and/or partial-face machine excavation are the likely choices for excavation of caverns and connections. Construction of these features can be accomplished with a minimum of interference with the tunnel boring operations. The amount of cavern excavation required will probably be much less than the tunnel excavation requirements, so cavern excavation is not expected to set the pace of the overall effort.

666. The number and size of shafts required is not known, but it is assumed that several shafts in the 10- to 20-ft-diam range would be required. Either drill and blast or large-diameter drilling or both are likely choices for shaft excavation. Concerns about inflows and cave-ins are eliminated with LDD, but drill and blast excavation is also quite reliable and versatile. Poor ground conditions can be handled by either method. Raise boring and reaming may be viable alternatives for shafts in the 10- to 12-ft-diam range.

667. It is considered unlikely that any of the novel excavation methods described in this report could be used alone to increase productivity or reduce costs. However, water-jets have demonstrated potential for increasing rates of advance of machine-driven tunnels. Drawbacks are increased mechanical complexity, power requirements, and the need for a large water supply.

668. Of the muck handling methods described in Part IV, rail haulage or conveyors are probably the best choices for the long main tunnels. For caverns, rail or rubber-tired equipment would be favored. Rail haulage is more economical for long hauls, but trucks offer more versatility, which may be advantageous for cavern construction. Alternatively, feeder conveyors

could be used to transport the muck to the main tunnel conveyor in a total conveyor system. Shaft hoisting using skips and a cable and winch system could provide the required capacity for muck removal both during shaft excavation and tunnel excavation.

669. Primary tunnel support could be provided by rockbolts and shotcrete, alone or in combination, as ground conditions dictate. This type of support is easily adapted to widely variable conditions and could result in savings in materials. Segmental concrete linings are versatile and allow steady, predictable installation rates, at the expense of extra materials used in the zones of favorable ground. Segments of variable thickness and reinforcement could be stockpiled and used as conditions change to save materials, but the extra storage space and decreased productivity occurring after each change might offset the savings in materials. Based on recorded experiences, shotcrete probably offers greater shock load resistance.

670. Grouting is the most likely choice for dealing with groundwater inflows and stability problems. Because of the highly specialized nature of grouting, specialists should be on hand to supervise grouting applications, including selection of materials and methods.

671. Auxiliary considerations, such as ventilation, alignment and grade control, instrumentation and monitoring, and health and safety have been discussed in this report. Implementation of these operations is fairly straightforward, but should be well-coordinated to produce a balanced, effective system. A well executed and documented instrumentation and monitoring program would provide valuable information and guidance for subsequent segments of the DB and for future projects, public or private.

672. Expertise and equipment required to build the DB facility are available. Because of the immense size of the planned facility, short-term shortages of some key personnel and skilled miners may be expected. However, if training is provided and financial incentives are strong enough, these shortages can be overcome. Short-term shortages of long-lead items may also be expected. Early planning and financial incentives for manufacturers could minimize this problem.

673. Short-term research, to be of the most benefit to the proposed project, should be directed at improvements in reliability and productivity of existing methods, meterials, and equipment for constructing tunnels and shafts.

Emphasis should be placed on improving components or operations that cause delays. For example, money spent on developing quickly placed precast concrete inverts with provisions for quickly connecting rail sections has paid off on some recent long tunnels. Faster rail haulage speeds and less downtime from derailments have resulted in savings of time and money. Muck hoisting efficiency in shafts may be improved significantly by using new high-capacity hoisting systems, compared to the use of old or used equipment, which is common in mining. The efficient muck handling system developed by a contractor on the TARP tunnels proves this. This system was so successful that it has since been used on an underground parking garage excavation project. On the other hand, research into novel or experimental excavation methods offers little promise for significant increases in productivity and reductions in cost. Significant savings do not appear likely by substitution of recently developed muck handling methods, i.e., pipeline systems, for rail, conveyor, or rubber-tired systems.

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APPENDIX A: SPECIFICATIONS FOR EXCAVATION AND MUCK HANDLING EQUIPMENT

APPENDIX A

SPECIFICATIONS FOR EXCAVATION AND MUCK HANDLING EQUIPMENT

Table of Contents

Page

I. EXCAVATION EQUIPMENT

II. MUCK HANDLING

*Note: Some manufacturers and specifications may have been inadvertently omitted. Equipment specifications for rubber-tired and crawler-mounted mucking units were unavailable for inclusion in the Appendix. Likewise, no specifications were available for conveyors and pipeline mucking systems. Pages 16-80 in this Appendix were taken from the Handbook of Mining and Tunneling Machinery, Stack (1982), with permission of John Wiley and Sons, Ltd. Permission to use this material is gratefully acknowledged.

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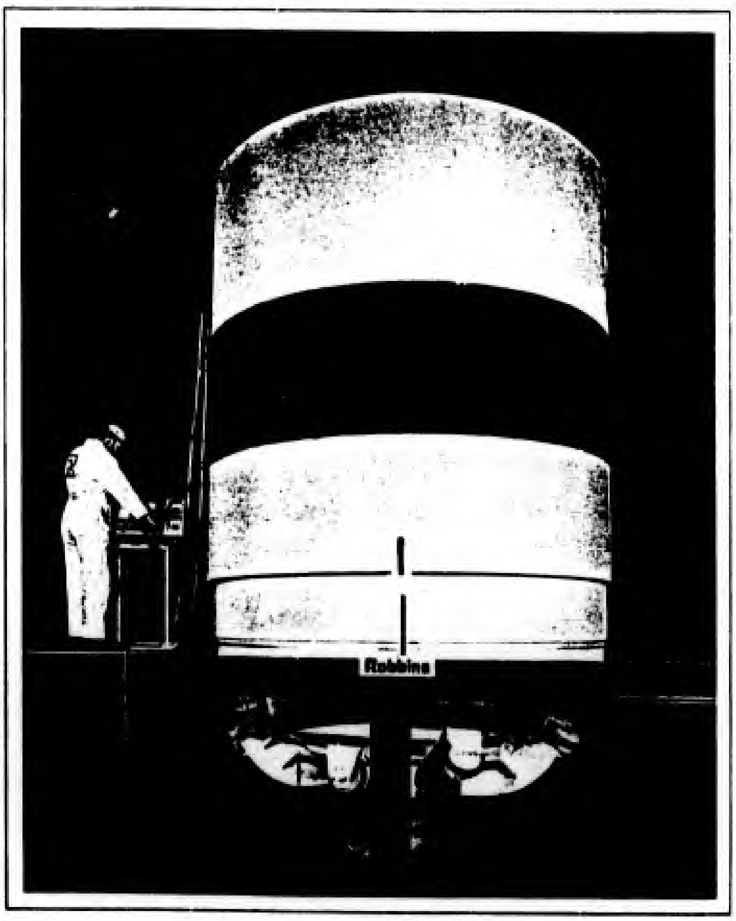
model

1211SR-194

Robbins Shaft Reamer

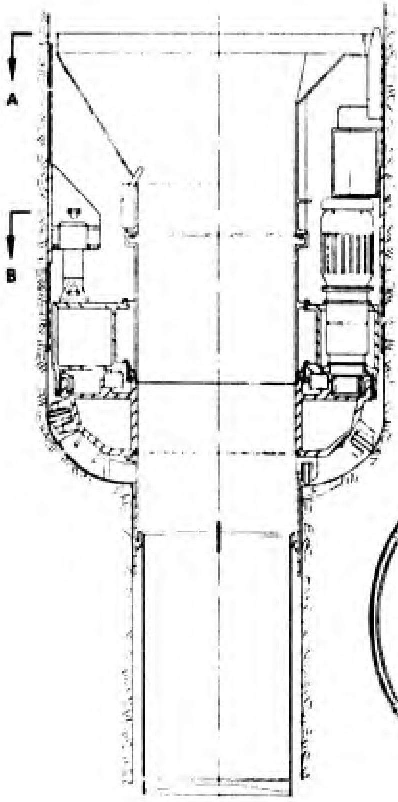


Project Information:

LOCATION	Sewer Vent and Drop Shafts/Chicago, Illinois
MATERIAL	Dolomitic Limestone
COMPRESSION	15 - 30 ksi (1050 - 2100 kg/cm^2)
SHAFT DEPTH	250 ft (76,2 m)

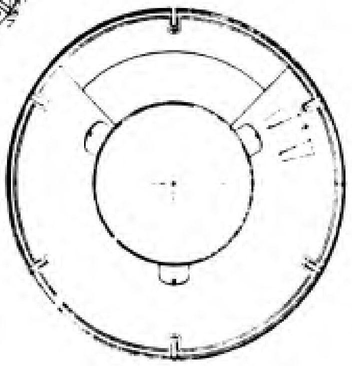
The Robbins Company 650 S. Orcas St. Seattle, WA 98108, USA Phone: (206) 767-7150 Cable: ROBBORING SEA Telex 32-871

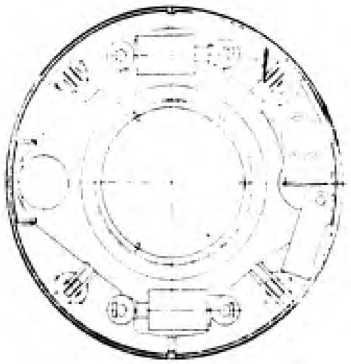
model 1211SR-194



Specifications:

TYPE	Shaft Reamer
DIAMETER	12 ft. (3,64 m)
HORSEPOWER	250
THRUST	375,000 lbs (170.100 kg)
WEIGHT	60 tons (54,36 metric tons)
CUTTERS	16 - 12 in. (30,5 cm) Diameter Disc Cutters


SECTION A-A


SECTION B-B

Features:

1. Domed cutterhead with pilot cylinder for stability.
2. Twin electric drive motors linked to speed reducers, both driving on a common ring gear, provide a rugged, efficient cutterhead drive system.
3. Pressure-lubricated double sealed anti-friction main bearing absorbs high cutterhead loads.
4. Robbins 12-inch disc cutters for high penetration rates in hard rock.
5. Pilot cylinder keeps the machine on line with the previous bored 6 foot pilot shaft.
6. Fast regripping cycle.
7. A scraper system on the cutterhead moves cuttings toward the center of the head where they are collected in a muck bucket suspended in the pilot hole below the machine.
8. Low pressure hydraulic system for long component life, low heat generation.
9. Machine is completely operated by remote control from the surface.
10. Expanding upper shield grips the shaft walls for thrust reaction. Telescoping forward shield has one foot stroke.

Robbins Reamers and Disc Cutters

FOR FAST PENETRATION AND LOWER COSTS IN SOFT TO MEDIUM HARD ROCK RAISES

Advantages of Robbins Domed Reamer

- Dome shaped reamer is self stabilizing for easier hole collaring and longer cutter life
- Available in sizes from 60 in. (1520 mm) to 144 in. (3657 mm)
- Removable stinger allows easier transport of reamer body in restricted areas
- Stinger can be replaced without replacing reamer body
- Non-welded stinger is built of high alloy - high strength non-weldable steel

Advantages of Robbins Disc Cutters

- Faster penetration rate
- Low initial cost, low operating cost
- Inexpensive replaceable cutting disc
- Produces large chips with fewer fines
- Lifetime lubrication eliminates maintenance during operation

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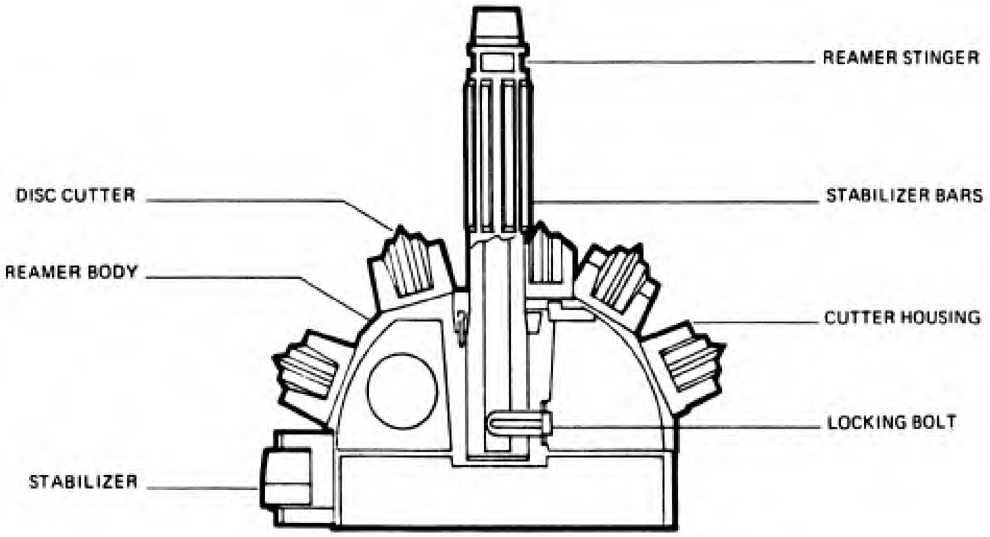
The Robbins Company 650 S Orcas St. Seattle, WA 98108, USA Phone (206)767 7150 Cable ROBBORING SEA Telex 32 8711

Domed Reamer With Disc Cutters



DOMED REAMER

The Robbins domed reamer is built with a removable stinger. This allows use of a long stinger providing added reamer stabilization. With the stinger removed the reamer body can be transported into restricted areas. The stinger is much stronger than those in permanently welded reamers, because high alloy, non-weldable steel can be used. It is unnecessary to handle the reamer body to replace or repair a damaged stinger. The domed shape of the Robbins reamer makes it self centering and very stable in the hole, minimizing cutter washing and increasing cutter life. Robbins reamers fitted with disc cutters have established world records for speed and economy in many rock types.

DISC CUTTERS

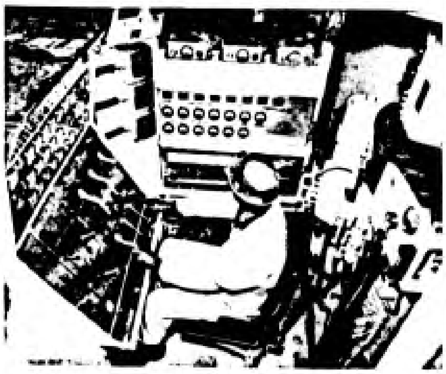
Robbins disc cutters offer an economical alternative to carbide and tooth type big-hole cutters. Proven economical in quartzites, granites and dolomites, the disc cutter reamer is even more advantageous in the softer rocks. Disc cutters fracture out large chips for faster penetration with fewer fines. Disc cutters cost less than one third the price of insert cutters. The replaceable ring on the disc cutter costs one fifth the price of the cutter assembly itself. Several replaceable rings can be installed on a bearing assembly before it requires service. Metal to metal seals keep oil in bearings and keep the dirt out. The same hub assembly can be refurbished several times by simply replacing the insert type bearings and seals.

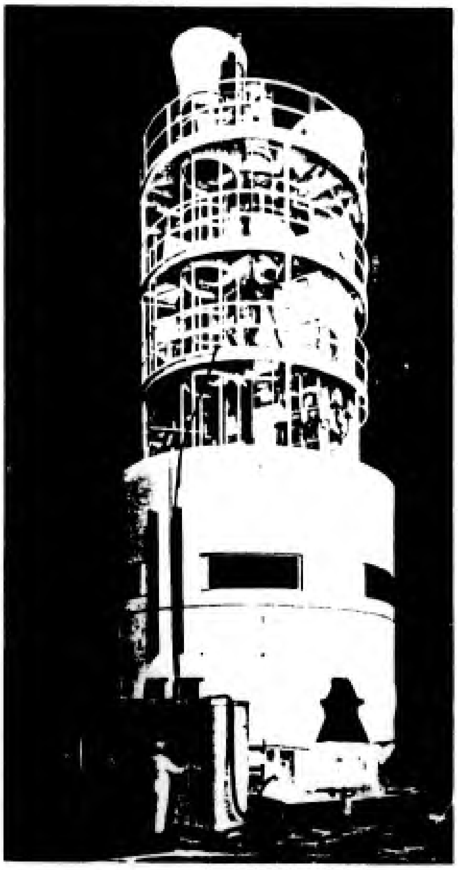
DRC 9-74

model

241SB-184 Robbins Blind Shaft Boring Machine

HARD ROCK
ROTARY MACHINE
DIAMETER 24 ft 5 in. (7,4m)



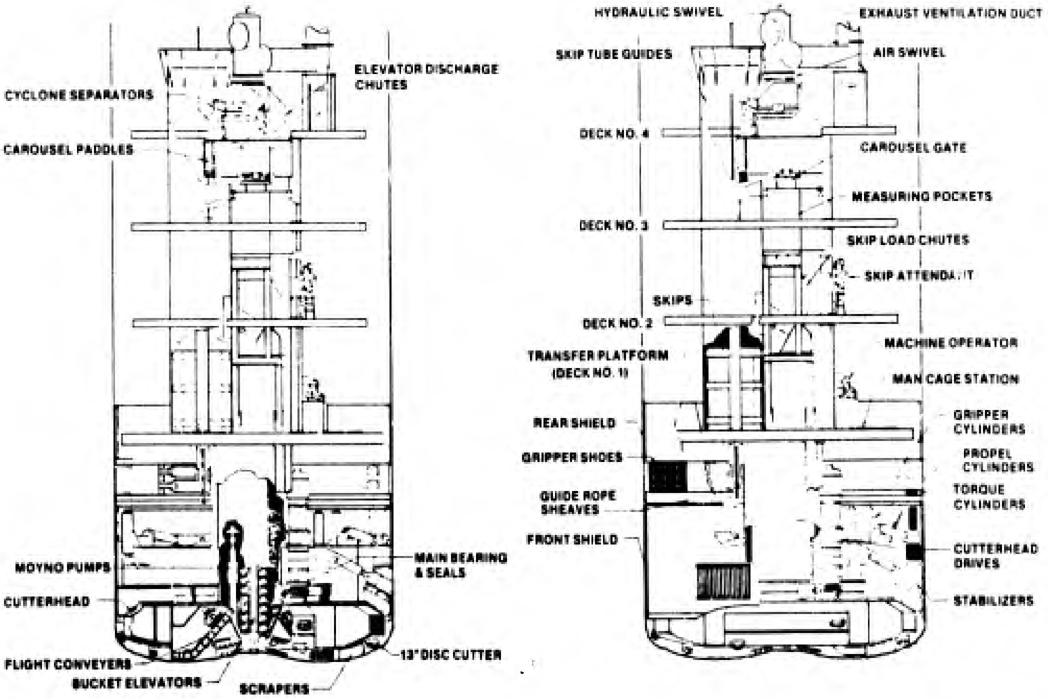


Project Information:

GENERAL	Designed, manufactured and demonstrated under contract from the United States Department of Energy
LOCATION (Demonstration Project) ·	Near Bessemer, Alabama
MATERIAL	Sandstone, interbeds of Shale and Sandy Shale
COMPRESSION STRENGTH	15-29 ksi (1055-2040 kg/cm^2)
SHAFT LINING	Cast concrete, jump form
SHAFT DEPTH	1160 ft (353,5 m)

The Robbins Company 650 S Orcas St Seattle WA 98108, USA Phone (206)767 7150 Cable ROBBORING SEA Telex 32 8711

model 241SB-184



ROTATING COMPONENTS

NON-ROTATING COMPONENTS

Specifications:

TYPE	Hard Rock Rotary Machine
DIAMETER	24 ft 5 in. (7,4 m)
HORSEPOWER	Drive – 750; Auxiliary – 305
THRUST	1,430,000 lbs (648,000 kg)
TORQUE	2,060,000 ft-lbs (285.000 kg-m)
WEIGHT	300 tons (272 metric tons)
CUTTERS	56 – 13-in. (33 cm) Diameter Steel Disc Cutters

Features:

1. The muck handling system is mechanical. Scrapers on the face of the cutterhead move muck to horizontal flight conveyors which feed bucket elevators. The bucket elevators dump into two measuring pockets near the top of the machine which in turn feed conventional skips running to the surface.

2. Robbins 13-in. (33 cm) disc cutters provide rapid penetration and produce muck with fewer fines for better handling. Cutters are changed from the back of the cutterhead for safety.

3. Rugged proven cutterhead drive featuring six AC motors with integral clutch and gear box driving a common ring gear.

4. Pressure-lubricated, sealed, double-roller main bearing absorbs high cutterhead loads.

5. Incorporates a permissible electrical system and fire-resistant hydraulic fluid for coal mine operation.

6. Modular construction facilitates mobilization in the shaft collar and removal from the shaft bottom.

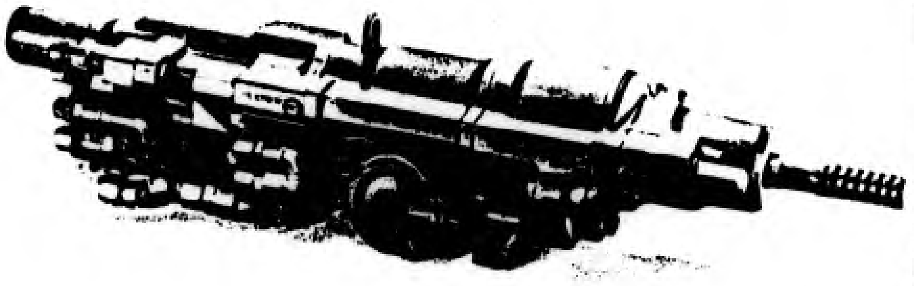
7. Dual laser guidance system and precision three-point steering system provide straight bore with minimum tolerance.

8. Large gripper area for operation in poor rock.

9. Full shield provides protected, clean work area for the miners.

COP 1038HD

Heavy, hydraulic rock drill for mechanized drifting with R38 rods. Hole diameters from 38 to 51 mm



Features

- Long slender piston matched to the drill steel permits optimal impact power without damaging the drill steel.
- Built in recoil dampener contributes to improved drill-steel economy and reduces wear on rock drill, feed and boom.
- Adjustable stroke length makes it possible to adjust impact rate and energy to actual rock conditions and hole size.
- Separate reversible rotation motor with steplessly variable rotation speed.
- Pressurized fronthead lubricates the shank adapter and prevents dirt and water from entering the rock drill.
- External sealed off water flushing for pressures up to 13 bar ensures efficient removal of cuttings and better bit life.
- The low profile of COP 1038 HD permits drilling close to the wall with a minimal look out angle.

Standard versions

	Product No.
COP 1038HD	8311 1038 01
COP 1038HD (HFC version)	8311 1038 01

Technical data

Length (excl. adapter)	mm	970
Width (incl. connections)	mm	260
Height over drill centre	mm	82
Weight	kg	142
Impact power	kW	15
Impact rate	Hz	42—60
Rotation speed	rpm	0—300
Rotation torque (max)	Nm	245
Working pressure	bar	150—250
Electric power consumption for pump motor in BHU 38	kW	45
Flushing water consumption (6 bar)	l/min	35
Water pressure	bar	4—13
Lubrication air requirements at 2 bar	l/s	2.5
Shank adapter	R38	

Hose dimensions

Oil to impact mechanism	mm	12.5
Oil from impact mechanism	mm	19
Oil for rotation (2)	mm	12.5
Flushing water	mm	20
Lubricating air	mm	6.3
Drainage	mm	6.3

COP 1038HD

Hydraulic drifter feeds

		BMH 612	BMH 614	BMH 616	BMH 618
Product number		8322 1104-72	8322 1104-30	8322 1104-98	8322 1104-56
Drill steel length	mm	3700	4305	4915	5525
Feed travel length (max drill depth)	mm	3405	4005	4615	5235
Total length	mm	5295	5895	6505	7125
Net weight	kg	360	380	400	420
Feed force	kN	12.5	12.5	12.5	12.5
Feed beam—standard		light alloy	light alloy	light alloy	light alloy
—optional		steel	steel		steel

Suitable booms: Tunmec R 315H*, BUT 10*, BUT 15, BUT 30

* Only for BMH 612, 614

Sandvik Coromant drill steel equipment

Drifter rods R38—R32

Length mm	ft	in	Part No Single thread	Part No Double thread
3700	12′	1¹/₂″	7854 3737-20	7854 3737-22
4305	14′	1¹/₂″	7854 3743-20	7854 3743-22
4915	16′	1¹/₂″	7854 3749-20	7854 3749-22
5525	18′	1¹/₂″	7854 3755-20	7854 3755-22

Shank adapter 7804 3590-01
(R38 female, length = 462 mm)

R32 cross bits and button bits

Dim mm	Part No Cross bit Normal	Part No Cross bit Heavy Duty	Part No Button bit
45	7733 1045-11	7733 1345-42	7733 6145-40
48	7733 1048-11	7733 1349-42	7733 6148-40
51	7733 1051-11	7733 1351-42	7733 6151-40
51	—	—	7733 6651-40
76	—	—	7733 6676-40*

* For cut holes

Reaming equipment, bits and pilot adapter R32

Bit dim mm	Part No	Pilot hole min, mm	Part No Pilot adapter R32
89	7721 6489-40	43	7821 3440
102	7721 6402-40	43	7821 3440

Drifter rods R38—R28

Length mm	ft	in	Part No Single thread
3700	12′	1¹/₂″	7854 2937-20
4305	14′	1¹/₂″	7854 2943-20
4815	16′	1¹/₂″	7854 2949-20

Shank adapter 7804 3590-01
(R38 female, length = 462 mm)

R28 cross bits and button bits

Dim mm	Part No Cross bit Heavy duty	Part No Button bit
38	7739 1438-42	7739 6138-40
41	7739 1441-42	7739 6141-40
43	7739 1443-42	7739 6143-40

Reaming equipment, bits and pilot adapter R28

Bit dim mm	Part No button bits	Pilot hole min, mm	Part No Pilot adapter R28
76	7722 6676-40	38	7821 1435
89	7722 6689-40	38	7821 1435

Atlas Copco

E 11209

The manufacturer reserves the right to make modifications without prior notice.

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-Hydraulic Drill Specifications

Manufacturer/Model No.		Rock Drill		Drill Piston						Drill rotation				Feed Thrust			
		Wt. (lb)	Length (in.)	Blows/ min.	Ft-lb/ Blow	Stroke (in.)	Hyd. Pres. (psi)	Total Energy/ min	Special Features	Rpm Range	Torque Range (ft-lb)	Hyd. Pres. (psi)	Method	Max. Fwd. (lbs)	Max. Ret. (lbs)	Hyd. Pres. (psi)	Special Features
Linden Alimak	Aidrill 101	253	34 2	3400	145	2	1750	493 000	Single internal valve	0-230	175	1750	Hydraulic motor chain feed	1800-2400	1800-2400	1820	Auto feed stop and retract
	Aidrill 102	290	43 5	3240	170	2	1950	550 800	Single internal valve	0-230	190	1950	Hydraulic motor chain feed	1800-2700	1800-2700	1820	Auto feed stop and retract
Atlas Copco	COP-1038 HD	320	38 8	2300-3600	185-260	2 68 max	2180-3630	598 000-666 000	3 piston stroke settings	0-300	18-479	1300	Hydraulic motor and hydraulic cylinder to cable	2800	2800	750-1300	Auto feed stop and retract
	1032 HD	220	32 2	—	—	—	3500	—	Medium duty	0-300	—	—	—	—	—	—	—
	1022 HD	88	24 4	3200	77	—	1000	246 400	Light duty	0-300	—	—	—	—	—	—	—
Secoma	RPH 200	198	24 0	2000-4000	72-144	0 5	2844	288 000 455 400	Variable energy and blow frequency	0-250	144-217	2875	Hydraulic cylinder	1731	904	1138	Auto feed stop and retract
	RPH 400	397	32 0	1800-3300	145-253	1	1850-2560	478 500	Variable energy and blow frequency	0-300	144-290	2000	Hydraulic cylinder	4410	2072	1422	Auto feed stop and retract
Gardner-Denver	HPR 1	325	43 75	2500-4000	125-200	1-2	2600	500 000	Variable stroke from the console	0-200	150	1400	Hydraulic cylinder or hydraulic motor and chain	3000	5000	2000	Auto feed stop and retract
Ingersoll-Rand	HARD III	545	39 4	9300	55	0 5	2600	511.500	Valveless, hyd oil acts as spring for power stroke	0-240	180-360	700-2000	Hydraulic cylinder	6000	4000	3000	Auto feed stop and retract
Jarvis-Clark/ Montabert	H70	271	37 0	2800	210	0 94	1840	588 000	Auto balance between impact and rotation	120-240	50-300	2200	Hydraulic cylinder and chain	2000	1500	3000	Auto feed stop and retract
Joy	JH2 120075	340	24 0	12000	75	0 5	2000-3000	900 000	Valveless, self-lubricated	60-500	150-500	500-1500	Hydraulic motor and chain	3000	6000	2200	Auto feed stop and retract
	105090	340	24 0	10000	90	0 7	2000-3000	900.000	Valveless, self-lubricated	60-500	150-500	500-1500	Hydraulic motor and chain	3000	6000	2200	Auto feed stop and retract
	060150	340	24 0	6000	150	1 0	2000-3000	900 000	Valveless, self-lubricated	60-500	150-500	500-1500	Hydraulic motor and chain	3000	6000	2200	Auto feed stop and retract
	JH3	230	22 0	9000	65	0 6	2000-3000	585.000	Valveless, self-lubricated	60-500	150-500	500-1500	Hydraulic motor and chain	2500	5000	2200	Auto feed stop and retract
Leroi-Dresser	LHD 155	297	28 0	2000	350	1 25	2000	700 000	—	150	240	2000	Hydraulic motor and chain	3000	3850	2000	—
SIG	HBM 100 I	275	30 0	4500	—	—	2560	—	—	400	229	1706	Hydraulic cylinder	1000	—	—	Auto feed stop and retract
	HBM 100II			3100						270	369	—	—	2205	—	—	Auto feed stop and retract
Tamrock	HL 438 T	247	31 5	3600	210	1 25	2400	756 000	Valveless, auto rotation reversal	0-300	0-96	2400	Hydraulic motor and chain	3500	2600	1100	Auto feed stop and retract

–Hydraulic Drill Specifications

	Hydraulic System			Drill Hole Flushing				Chassis or Carriage (Continued on Table 3)							
Manufacturer Model No.	No. of Pumps/ Drill	Pump Type	Description of System	Method	Method of Application	Flush. Pres. (psi)	Flush. Flow (gpm)	Model No.	Carriage Description	Boom Description	No. of Booms	Face Coverage	Length of Hole	Drill Steel	Striking Bar
Alimak 101	1	Axial piston	Closed loop each drill water cooled	Water flushing	Through drill	115-175	8	H832A Alimatic	4-wheel drive, articulated steering	Boom and feeds rotate or slew	1 or 2	16.4(H) × 23(W) ft	11.5 ft	1-in -diam 1¼-in -diam	1½-in rope male thread
Alimak 102				Water flushing	Through drill	115-175	11.2	H832 Alimatic	4-wheel drive, articulated steering	Boom and feeds rotate or slew	1 or 2	16.4(H) × 23(W) ft	11.5 ft	1-in -diam 1¼-in -diam	1½-in rope male thread
Atlas Copco 1038HD	2	Variable displacement piston	Closed loop-each drill	Water, vapor-mist, or oct	Front head flushing	100-200	14	Eaton Yale EC-4	4 wheel drive, articulated steering	But 10-F, telescopic feed, parallel holding	1, 2, or 3	15(H) × 20(W) ft	Up to 16.5 ft	1¼-in hex	1½-in rope male thread
Secoma RPH200 RPH400	Information not complete for marketing reasons		—	Water or vapor	Through drill	142 140	17 7	—	—	—	Variable	—	—	—	1½-in rope, male thread
Gardner-Denver HPR1	1	Axial piston	Closed loop-each drill air cooled	Water or air	Through drill	125	15-25	Gardner-Denver Mark III	Rigid frame, rear wheel steel, 4-wheel drive	J11 HD booms, roll over parallel extendable available	1, 2, or 3	18.8(H) × 31.5(W) ft	Up to 16 ft	1¼ in round 1¼-in hex 1½-in round	1½ in rope Hi-lead or T38 male thread
Ingersoll-Rand Hard III	2	Variable displacement piston	Double network-water cooled, closed system	Water or vaposol	Through drill	100-110 min.	8-15	96RMH	4 wheel drive, articulated steering	Roll-over parallel extendable	2	25(H) × 42(W) ft	12 ft	1¼-in hex 1¼-in round	1½-in rope female thread
Jarvis-Clark M-H70	1	Tandem gear	Closed loop-each drill	Water or air	Through drill	150 max	10	ECI Minejack	4-wheel drive, articulated steering	Roll-over extendable	2 or 3	14(H) × 22(W) ft	10-18 ft	1¼-in hex 1¼-in round	1½-in rope, male thread
Joy JH2	1	Positive displacement gear	Single network-open loop water cooled	Water or air	Through drill	150 max	15	DPH	4 wheel drive, articulated steering	Roll-over or crossover, ex-tend or fix paralleling	2	21.5(H) × 36(W) ft	Up to 20.5 ft	1¼-in round 1½-in round	1½-in rope male thread
Joy JH3	1	Positive displacement gear	Single network-open loop water cooled	Water or air	Through drill	150 max	15	DPM	Frame steering, 4-wheel drive	Roll-over or crossover, ex-tend or fix paralleling	2	19(H) × 30(W) ft	Up to 15 ft	1¼-in round	1¾-in rope thread choice
LeRoi LHD155	1-3 sec	Positive displacement gear	Closed loop with cooler	Air	Through drill	100	175 cfm	HDR12EH	Vertical track drill	—	1	16(H) × 20(W) ft	11 ft	1½-in diam 1¾-in diam	1½- or 1¾-in rope
SIG HBM100	—	—	—	Water	Through drill	142	9	—	—	—	1 to 3	—	—	—	—
Tamrock HL438T	1	Positive displacement gear	Closed loop-each drill water cooled	Water or vapor	Through drill	90-150	9	Eaton Yale or Getman	4-wheel drive articulated steering	Base roll-over, extend paralleling	1 to 3	20(H) × 35(W) ft	18 ft max	1¼-in -diam 1½-in -diam	1¼- or 1½-in rope, male thread

-Hydraulic Drill Specifications

	Chassis or Carriage (Continued from Table 2)							Electric Motors for Hydraulic System						
Manufacturer Model No.	Carriage Motor Specs	Length (ft)	Height (ft)	Width (ft)	Wheel Base (ft)	Total Weight (lb)	Method of Illumination	Number/ Drill	Class	Voltage	Amperage	H.P.	Power Requirements (amps)	Operating Sound Levels
Alimak 101	Deutz F3L-912W	37'	8.2	6.1	10'6"	12,000	Tungsten halogen	1	TEFC	440	80	50	95 each	102 dBA - distance not known
Atlas Copco 103BHD	Deutz F6L-912W	34'3"	8'10"	8'3"	11'11"	54,000	Two 55-W sealed beam or tungsten halogen available	One each boom plus compressor motor	TEFC	480	90	75	75 90 each	102-106 dBA @ 3 m from drill
Secoma RPH200	—	—	—	—	—	—	—	—	—	—	—	—	—	103 dBA @ console
RPH400	—	—	—	—	—	—	—	—	—	—	—	—	—	107 dBA @ console
Gardner-Denver HPR1	Deutz F6L-912W	37'	8.0	7.75	9'0"	41,000	Two 300-W incandescent or tungsten halogen	1	TEFC	480	90	75	68 each	109 dBA @ 7 m from drill
Ingersoll-Rand HARD III	Deutz F6L-912W	44	7'8"	9'10"	10'5"	49,900	30-W sealed beam	1	TEFC	480	90	75	198 total	103 dBA @ console
Jarvis-Clark H70	Deutz F6L-912W	40'5"	8.0	8'6"	9'10"	36,000	12-V sealed beams	1	TEFC	600	45	50	45 each	108 dBA @ console
Joy JH2	Cat 3306	43'6"	11'2"	9.0	11'9"	57,000	Tungsten halogen	1	TEFC 1.15 serv factor	440	92	75	100 total 120 max	100 dBA—1 drill 103 dBA - 2 drills @ console
Joy JH3	Deutz F6L-912W	33'8"	Top of canopy 10'3"	8.0	10'5"	36,000		1	TEFC 1.15 serv factor	440	60	50	68 total 78 max	99-101 dBA @ 1 m
LeRoi LHD155	Deutz F4L-912	17'11"	6'9"	8.0	7'4"	19,900	None	None	—	—	—	—	—	97 dBA @ 7 m
Sig HBM100	—	—	—	—	—	—	—	—	—	—	—	—	—	98 dBA - distance not known
Tamrock HL438T	Deutz F6L-912W	39	8.0	8.0	9'9"	44,000	Tungsten halogen	1	TEFC	480	62	50	62 max	108 dBA @ 9 ft

Flow Jet-Miner Specifications

Jet-Miner™

Tool Weight	8 lbs.	Working Pressure	30,000-55,000psi	Tool Stem Length/Weight:	
Noise Level	88 dbA	Nozzle Flow Rate:		6'-2"	6 lbs.
Rotation	Air Motor, 20 cfm	35,000 psi	2.5-3.0 gpm	8'-3"	8 lbs.
		55,000 psi	1.6-2.0 gpm	10'-4"	10 lbs.

Telescopic Feedleg, Pneumatic, 10' Extension

Weight	16 lbs.	Length Collapsed	6'-2"	Thrust	150-250 lbs.

High-Pressure Water Hose

	Size 5	Size 8		Size 5	Size 8
Working Pressure	36,000 psi	33,000 psi	Weight per 50'	15 lbs.	22 lbs.
Burst Pressure	64,000 psi	58,000 psi	Max. Working Flow	3 gpm	8 gpm
Outside Dia.	.50"	.62"	Max. Working Length	200'	500'

Jet-Pac™ Powerpack Pump Module Options

HPM-40, 0-3 gpm, 0-40,000 psi

HPM-55, 0-2 gpm, 0-55,000 psi

Electric Jet-Pac™, Complete with 75 Horsepower Motor

Weight	3550 lbs.	Length	108"	Width	36"
Height	44"	Frame	Roll Bar	Mounting	Skids

Diesel Jet-Pac™, Complete with Deutz Engine

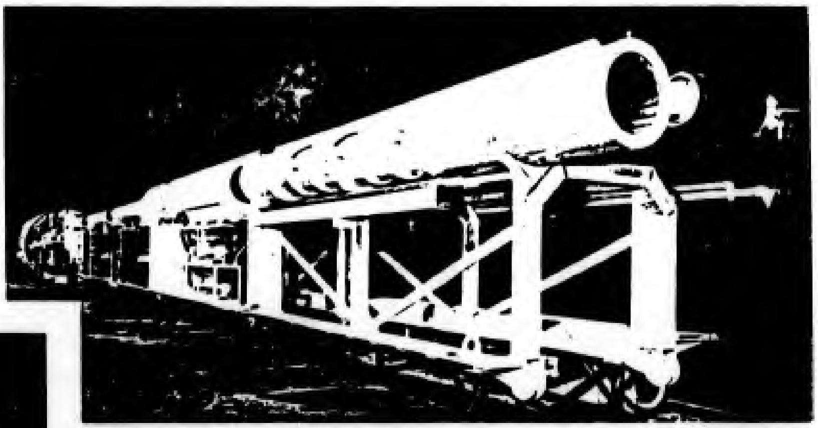
Engine	F6L413, V-6	Weight	5,300 lbs.	Height	48"
Horsepower, sea level	139	Width	48"	Length	124"
Horsepower, 9000' elev.	93	Frame	Roll Bar	Mounting	Skids

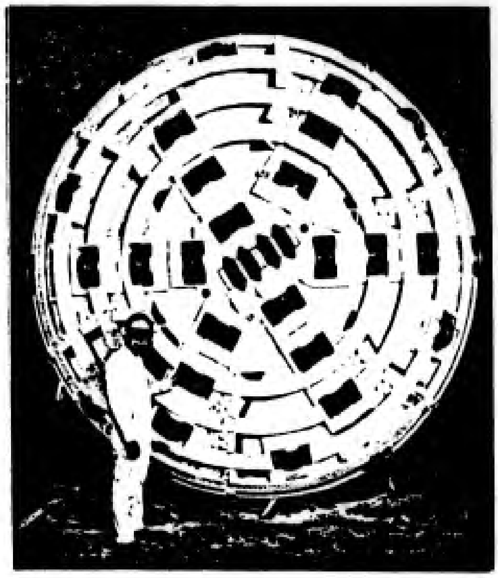
model

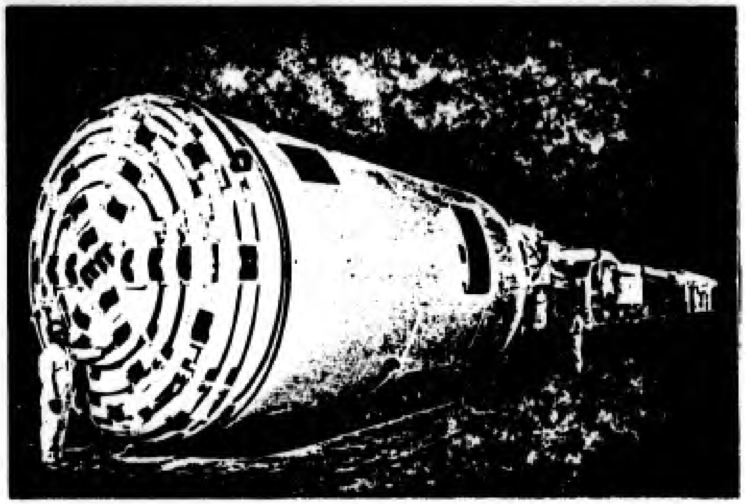
151-191

Robbins Tunnel Machine

SHIELDED
HARD ROCK
ROTARY MACHINE
DIAMETER
14 ft 11.5 in. (4,56m)





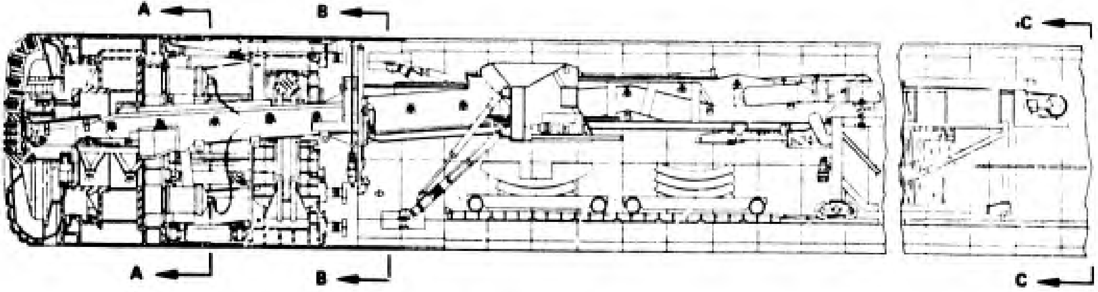


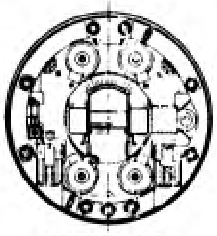
Project Information:

LOCATION	Central Siberia, U.S.S.R./RR Pilot Tunnel
MATERIAL	Granite
COMPRESSION	4-26 ksi (300-1800 kg/cm^2)
SUPPORT	Segments/Ring Beams/Roof Bolts with/or without Mesh/Shotcrete
TUNNEL LENGTH	16,000 ft (4.990 m) Initial Section

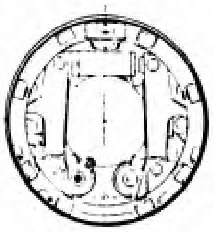
The Robbins Company Box C8207, 7615 S. 212th St. Kent, WA 98031, USA Phone (206) 872-0500 Cable ROBBORE KENW Telex 32-8711

model 151-191

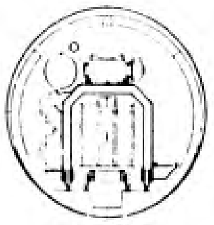




SECTION A-A



SECTION B-B



SECTION C-C

Specifications:

TYPE	Shielded Hard Rock Rotary Machine
DIAMETER	14 ft 11.5 in. (4,56 m)
HORSEPOWER	Cutterhead - 800 HP; Total Connected – 1200 HP
THRUST	2,702,900 lbs (1.226.000 kg)
WEIGHT	230 tons (210 metric tons)
CUTTERS	2 – 12 in. (30,5 cm) Twin Disc Center Cutters 30 – 14 in. (35,6 cm) Diameter Steel Disc Cutters

---

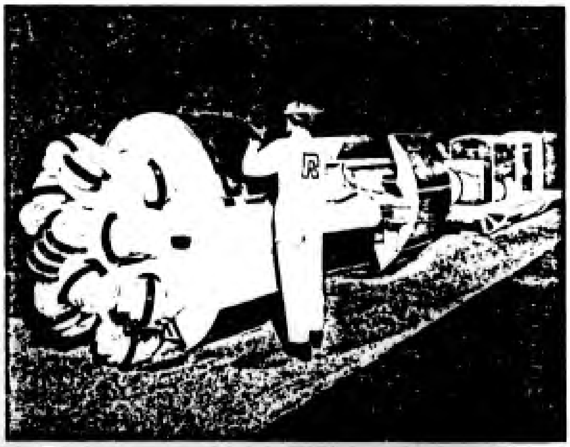
Features:

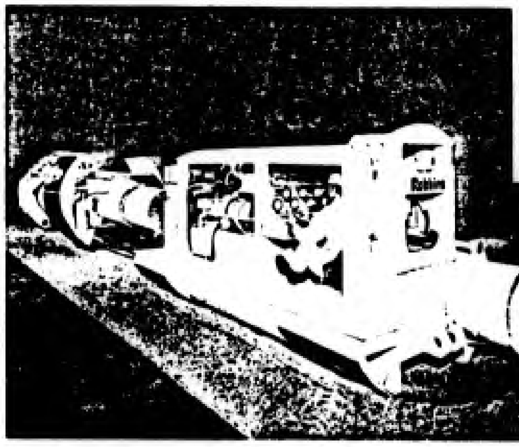
1. Center discharge cutterhead with radial scoops and muck openings.
2. Wide radial spokes provide rigid mounting for the disc cutters.
3. Disc cutters can be changed from the rear of the cutterhead.
4. Two piece, articulated telescopic shield for ease of steering and protection from heavy ground.
5. Quadrant steering of front shield for precise line and grade control. Cutterhead elevation adjustment for trim control.
6. Full thrust from wall gripper. Auxiliary liner thrusting system.
7. Multiple two-speed electric motors with clutches linked to speed reducers, all driving on a common ring gear, provide a rugged, efficient cutterhead drive system.
8. Pressure-lubricated double sealed anti-friction main bearing transmits high cutterhead loads.
9. Robbins high-capacity 14-inch diameter disc cutters for high penetration rates in hard rock and maximum cutter life.
10. Fast retract system resets gripper shield quickly.
11. Low pressure hydraulic system for long component life, low heat generation.
12. Provision for roof bolting while machine is boring.
13. Segment erectors to install precast concrete segmental lining or precast invert and steel ring beams.
14. Trailing gantry contains the dust scrubber, provides space for rail installation, and includes the loading belt conveyor for loading muck cars.

model

61-176/177

Robbins Tunnel Machine





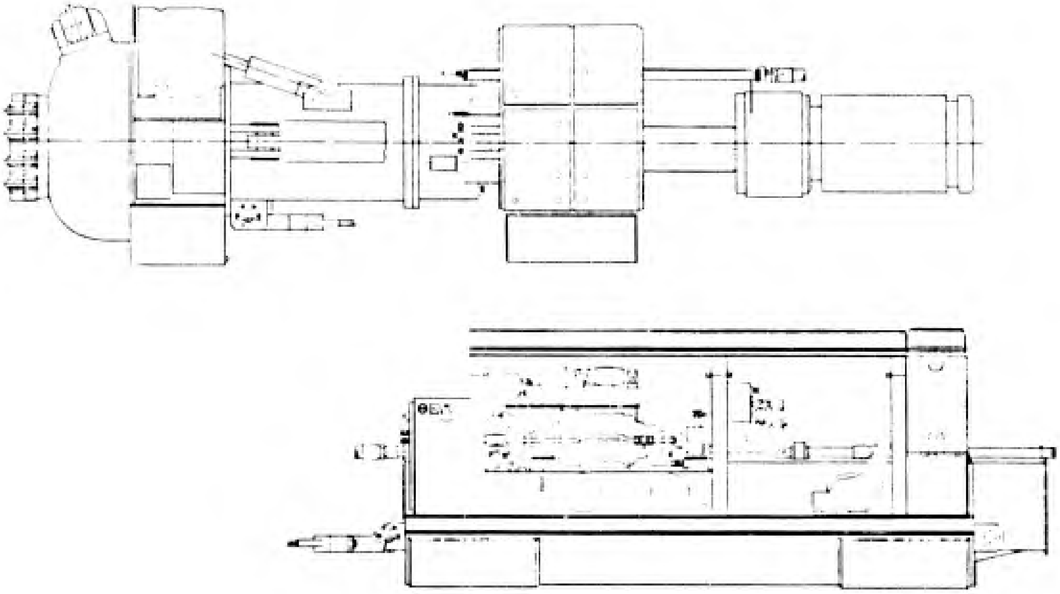
INCLINED BORING MACHINE
DIAMETER 6 ft. 1/2 in. (1,84m)

Project Information:

LOCATION	East Driefontein Mine/Carltonville, South Africa Blyvoor Mine/Blyvoor, South Africa
MATERIAL	Quartzite
COMPRESSION	25 ksi (1750 kg/cm^2)
TUNNEL LENGTH	Continuous Operation

The Robbins Company 650 S. Orcas St. Seattle, WA 98108, USA Phone (206) 767-7150 Cable ROBBORING SEA Telex 32-8711

model 61-176/177



Specifications:

TYPE	Inclined Boring Machine
DIAMETER	6 ft 1/2 in. (1,84 m)
HORSEPOWER	200
THRUST	445,320 lbs (201.997 kilos)
WEIGHT	15 tons (13,6 metric tons)
CUTTERS	Disc or Carbide Insert

Features:

1. Heavy domed cutterhead for rigid, stable running head.
2. Single electric motor linked to speed reducer, provides a rugged, efficient cutterhead drive system.
3. Pressure-lubricated double sealed anti-friction main bearing absorbs high cutterhead loads.
4. Robbins 12-inch high-capacity disc or carbide cutters for high penetration rates in all types of rock.
5. Hydraulically loaded roof shields support the crown of the tunnel and stabilize the machine.
6. Full floating gripper system permits steering during the boring cycle.
7. Low pressure hydraulic system for long component life, low heat generation.

hydraulic impact hammer.

SPECIFICATIONS

Impact class per blow	Over 2000 ft. lbs./276 mkg
Blows per minute	450, or 900 at half power
Impact class per minute	Over 900,000 ft. lbs./ Over 124,430 mkg
Weight with standard bracket	3250 lbs./1474 kg
Overall length	94 inches/239 cm
Required oil flow	30 GPM/114 LPM
Recommended minimum pump capacity	Varies with machine
Quick-change tool feature	Standard
Top-mounted brackets	Standard
Spacing inside mounting bracket	Varies with machine
Boom pin diameter	Varies with machine
Standard demolition tool	Chisel or Conical Point
Tool diameter	5¼ inches/133 mm
Tool working length	24 inches/610 mm
Operating pressure	2600 PSI/180 kg/cm²

The Hy-Ram 99 is also available in two heavy-duty versions, the 9901 and 9902. These models feature abrasion-resistant mounting brackets and longer working-length demolition tools. Contact the factory for further specifications.

Specifications are subject to change without notice.

Raise Drill Machines

Calweld-Smith Inc.

Model no.	Year of manufacture	Number of this model manufactured	Thrust kN (lb)	Nominal raise diameter m (ft)	Pilot drill diameter mm (in)
VTB	1967	12	356 (80,000)	To 1.32 (To 4′ 4″)	
BH-80-60	1974	4	1,668 (375,000) to 2,224 (500,000)		

Dresser Industries Inc. (Drilling Equipment Operations)

Model no.	Year of manufacture	Number of this model manufactured	Thrust kN (lb)	Nominal raise diameter m (ft)	Pilot drill diameter mm (in)
7200	1967		2,200 (500,000)	1.8 (6)	
480	1968-72	18	1,335 (300,000)	1.2-1.8 (4-6)	250.8-311.1 (9⅞-12¼)
800	1971-73	8	2,669 (600,000)	1.8-3.0 (6-10)	311.1 maximum (12¼)
500	1971-79	7	2,224 (500,000)	1.2-1.8 (4-6)	250.8-311.1 9⅞-12¼)
300	1972-79	7	800 (180,000)	0.91-1.2 (3-4)	250.8 nominal (9⅞)

Note: In 1964 Nichols Universal Drilling Co. built raise-boring machines Models RD1 and RD2 which were first used in the Cœur d'Alene mining district of Idaho and Anaconda in Butte, Montana. Subsequently Security Engineering of Dresser Industries purchased the Nichols assets in 1965. With previous experience in the manufacture of cutters and reamer heads the company was able to offer a complete raise drill equipment package. The company's name was then changed to Dresser Oil Field and Mining Equipment and later (approx 1971) to Dresser Mining Services and Equipment Division. Dresser's involvement in raise boring can be traced back to the application of cutters and the first raise-boring machine built by the Robbins Company.

Hughes Tool Company

Model no.	Year of manufacture	Number of this model manufactured	Thrust kN (lb)	Nominal raise diameter m (ft)	Pilot drill diameter mm (in)
MRD 100	1962		900 (200,000)	1.2 (4)	
MRD 100M	1965		900 (200,000)	1.2 (4)	
MRD 60	1966		900 (200,000)	1.2 (4)	
MRD 200	1967		900 (200,000)	1.2 (4)	
MRD 200M	1970		1,000 (225,000)	1.5 (5)	

Raise Drill Machines — continued

Ingersoll-Rand Company

Model no.	Year of manufacture	Number of this model manufactured	Thrust kN (lb)	Nominal raise diameter m (ft)	Pilot drill diameter mm (in)
RBM-7	1972	16	3,020 (680,000)	2.44 (8)	311 (12¼)
RBM-6	1974	8	2,130 (480,000)	1.83 (6)	280 (11)
RBM-211	1977	2	4,444 (1,000,000)	3.66 (12)	349 (13¾)

Note: Ingersoll-Rand Drill Division purchased by the Robbins Company, November 1979, now called 'Robbins Machine Incorporated & Products' sold under Robbins name.

Koken Boring Machine Company Limited

Model no.	Year of manufacture	Number of this model manufactured	Thrust kN (lb) (reaming pull)	Nominal raise diameter m (ft)	Pilot drill diameter mm (in)
BM-1	1967	1			
BM-100	1968	8			
BM-40	1969	2			
BM-200	1969	2			
Current models					
BM-50N	1970	18	441 (99,200)	0.5-0.8 (1.64-2.62)	200.0 (7⅞)
BM-100N	1971	14	1,570 (353,000)	1.15-1.45-1.75 (3.77-4.76-5.74)	250.8 (9⅞)
BM-150N	1971		2,160 (485,000)	1.75-1.83-2.13 (5.74-6.00-7.00)	270.0 (10⅝)
BM-200N	1970	2	2,750 (617,000)	1.83-2.13-2.43 (6.0-7.0-8.0)	349.3 (13¾)

Komatsu Limited (Robbins Company Licensee)

Model no,	Year of manufacture	Number of this model manufactured	Thrust kN (lb)	Nominal raise diameter m (ft)	Pilot drill diameter mm (in)
6ZRK	1973	1	1,372 (308,000)	1.5 (4-9)	Boring down 250 (0-10) Boring up 381 (1-3)

Raise Drill Machines – continued

The Robbins Company

Model no.	Year of manufacture	Number of this model manufactured	Thrust kN (lb)	Nominal raise diameter m (ft) (hard rock)	Pilot drill diameter mm (in)
31R (1101)	1962	1	n.a.	0.9 (3)	171.4 (6¾)
41R	1963	20	890 (200,000)	1.2 (4)	228.6 (9)
61R	1967	58	1,400 (315,000)	1.8 (6)	279.4 (11)
81R	1971	2	5,560 (1,250,000)	2.4-3.6 (8-12)	352.4 (13⅞)
71R	1972	23	2,520 (567,000)	2.4 (8)	279.4 (11)
11D (11MD)	1973	17	220 (49,308)	Rotary drill	200.0-250.8 (7⅞-9⅞)
32R	1973	4	800 (180,000)	1.2 (4)	228.6 (9)
23R	1974	2	340 (77,000)	0.9 (3)	200.0 (7⅞)
52R	1974	13	1,560 (350,000)	Blind hole 1.5 (5)	
72R	1974	7	2,730 (615,000)	2.1 (7)	279.4 (11)
82R	1974	5	3,340 (750,000)	2.4 (8)	311.1 (12¼)
84R	1974	3	3,340 (750,000)	2.4 (8)	311.1 (12¼)
33R	1975	1	3,400 (77,000)	Blind hole 0.9 (3)	
85R	1975	4	4,450 (1,000,000)	3.0-3.6 (1-12)	349.2 (13¾)
63R	1976	1	1,400 (315,000)	1.8 (6)	279.4 (11)
34R	1977	1	800 (180,000)	1.2 (4)	228.6 (9)
121R	1978	1	8,900 (2,000,000)	3.6 (12)	349.2 (13¾)
121BR	1978	1	5,560 (1,250,000)	Raise drill/ Blind-hole drill 4.5 (15)	558.8 (22)
80BR	1978	1	4,450 (1,000,000)	Raise drill/ Blind-hole drill 4.5 (15)	406.4 (16)
43R	1979	3	1,555 (350,000)	1.2-1.5 (4-5)	228 (9)

Raise Drill Machines — continued

Subterranean Tools Inc. (Division of Kennametal Inc.) now Subterranean Equipment Company

Model no.	Year of manufacture	Number of this model manufactured	Thrust kN (lb)	Nominal raise diameter m (ft)	Pilot drill diameter mm (in)
003	1971	6	400 (100,000)	0.9 (3)	200 (7⅞)
007	1971	3	2,200 (500,000)	2.1 (7)	
004	1972	12	900 (200,000)	1.2-1.5 (4-5)	228 (9)
005	1972	7	1,300 (300,000)	1.5-1.82 (5-6)	279 (11)
009	1973	7	3,100 (700,000)	2.13-4.57 (7-15)	279 (11) or 311 (12¼)
006	1974	n.a.	1,800 (400,000)	1.82 (6)	
010	1974	n.a.	4,400 (1,000,000)	3.7 (12)	
UR-60	1973	3		1.5 (5)	
UR-36	1975	1		0.9 (3)	

Note: One of the first machines built by Subterranean Tools Inc. in 1971 (Model 007) was installed in the Molybdenum mine in Colorado in September 1971. In 1973 Subterranean Tools Inc. became a wholly owned subsidiary of Kennametal Inc. Complete raise-boring systems were offered until 15 September 1978. That year Kennametal Inc. decided it would no longer participate in the rock-cutting machine market and a new company, Subterranean Equipment Company, was formed to service the customers of Subterranean Tools Inc. Although not affiliated with Kennametal Inc., Subterranean Equipment Company were given a non-exclusive distributorship for Kennametal cutters.

Tampella-Tamrock

Model no.	Year of manufacture	Number of this model manufactured	Thrust kN (lb)	Nominal raise diameter m (ft)	Pilot drill diameter mm (in)
1000E	1973-79	5	3,200 (719,000)	2.4[a]-3.7[b] (8-12)	280-311 (11-12¼)

Note: Initially Tamrock acted as the agent for Dresser Industries in Scandinavian countries but later started its own raise-boring machine programme.

[a] Hard rock

[b] Soft rock

Raise Drill Machines — continued

TURMAG Turbo-Maschinen AG — Sprockhovel/West Germany

Model no.	Year of manufacture	Number of this model manufactured	Thrust kN (lb)	Nominal raise diameter m (ft)	Pilot drill diameter mm (in)
PVI/120120	to 1965	240	120 (27,000)	0.6 (1.9)	143 (5.63)
P 600	from 1965	42	120 (27,000)	0.6 (1.9)	143 (5.63)
P 30	to 1968	108	250 (56,200)	1.2 (3.9)	193 (7.60)
P 1200	from 1968	60	250 (56,200)	2.4 (7.9)	193 (7.60)
EH 6000	from 1976	3	500 (112,000)	6.0 (19.7)	216 (8.50)

Raise and Box Drill Machines

Wirth Maschinen und Bohrgerate Fabrik GmbH
(Wirth Maschinen GmbH)

Model no.	Year of manufacture	Number of this model manufactured	Thrust kN (lb)	Nominal raise diameter m (ft)	Pilot drill diameter mm (in)
HG 160			863 (194,000)		
HG 210			1,569 (353,000)		
HG 250			2,648 (595,000)		
HG 170S					

Other manufacturers of raise drill machines not included in raise drill machine list: U.S.S.R.

Hard-rock Tunnelling Machines

Atlas Copco Maschinen AG (obtained Patent Rights from Habegger in 1968). *Medium to hard-rock circular and rectangular full-face and mini machines* (see also 'Habegger, Limited' machines)

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight (tons)
Circular FF 340 4/1967- 11/1967	Julia 1 Switzerland	Flysch 1,835-2,039 (180-200) 26,000-29,000	295 (968)	3.40 (11 2)				
FF 340 5/1968- 10/1968	Julia 2 Switzerland	Metam. schist 612 (60) 8,700	880 (2,887)	3.40 (11 2)				
FF 340 6/1969- 10/1971	Rorschach Switzerland	Sandstone 612-1,835 (60-180) 8,700-26,000	4,530 (14,862)	3.40 (11 2)				
FF 400 8/1973- 7/1975	Elikon -A Greece	Limestone 1,224-1,631 (120-160) 17,000-23,000	5,509 (18,075)	4.25 (13 11½)				
Circular FF 836 FF 840 FF 845 1967-74	Seikan Japan (machines manufactured by IHI — licence holder)		approx. 4,900 (16,076)	3.60 (11 10) 4.00 (13 2) 4.50 (14 9)				
FF 945	Seikan Japan			4.50 (14 9)				
FF 340				3.40 (11 2)				
Rectangular FF 4826 (Prototype) 10/1971- 6/1972	White Pine, U.S.A., copper mine		310 (1,017)	4.80 × 2.60 (15 9 × 8 6)				
Rectangular Mini FF Prototype 8/1971-4/1972	Rorschach, Switzerland	Sandstone 1,020-1,631 (100-160) 15,000-23,000	350 (1,148) 4 tunnels	1.30 × 2.10 (4 3 × 6 11)				
Mini FF 1524 7/1973- 10/1973 (Mini-0)	Innsbruck, Austria	Breccia limestone 306-510 (30-50) 4,400-7,200 1,427-1,835 (140-180) 20,000-26,000	400 (1,312)	1.50 × 2.40 (4 11 × 7 10½)				
Mini FF 1524 12/1973- 1/1974	Neuchâtel, Switzerland	Jura limestone 1,224-1,427 (120-140) 17,000-20,000	115 (377)	1.50 × 2.40 (4 11 × 7 10½)				
Mini FF 1524 3-5/1974	Rochester, U.S.A.	Dolomite limestone 1,276-1,428 (125-140) 18,000-20,000	204 (669)	1.50 × 2.40 (4 11 × 7 10½)				
Rect. Mini FF 1524 (Mini-0) 1/1976-3/1977	Trento, Italy (tunnel flooded 3/1977)	Dolomitic limestone	1,339 (4,390)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
12/1977- 2/1978	Balmholz II, Switzerland (conveyor-tunnel also tool test)	Limestone 3,060 (300) 44,000	90 (295)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		

Hard-rock Tunnelling Machines

Atlas Copco Maschinen AG. Medium to hard-rock circular and rectangular full-face and mini machines

Model type and year	Project location	Rock strength kg/cm² (MPa) lb/in²	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
5/1978	Laufenburg, Switzerland (Test)	Granite 3,000 (295) 43,500	11 (36)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
(Mini-1) 10/1974	Barden Road, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	425 (1,394)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
2/1975	Cotao, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	598 (1,962)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
11/1975- 1/1976	Forbes Creek, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	490 (1,610)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
3/1976- 5/1976	New Port, Sydney, Australia	Sandstone, shale 408-612 (40-60) 5,800-8,700	330 (1,083)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
6/1976	Avalon, Sydney, Australia	Siltstone mixed with sandstone 300-750 (30-74) 4,350-10,800	795 (2,607)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
(Mini-1) 12/1977	Drummoyne, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	1,182 (3,875)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
6/1978	Mill Creek, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	462 (1,514)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
11/1978	Forbes Creek II, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	511 (1,675)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
7/1979	Engadine III, Sydney, Australia	Shale, sandstone 300-500 (30-50) 4,350-7,250	647 (2,121)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
Rect. Mini FF 1524 (Mini-2) 8/1974- 10/1974	Washington Metro 1, U.S.A.	Shale 2,039 (200) 29,000	200 (656)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
11/1974	Washington Metro 2, U.S.A.	Shale 2,039 (200) 29,000	50 (164)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			
11/1975- 11/1976	Quincy, Ill., U.S.A.	Metamorphic limestone with layers of chert 1,630-1,840 (160-180) 23,000-26,000	2,385 (7,825)	1.50 × 2.40 (4 11 × 7 10½)	Not applicable			

Hard-rock Tunnelling Machines

Atlas Copco Maschinen AG. Medium to hard-rock circular and rectangular full-face and mini machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
Rect. Mini FF 1524 (Mini-3) 8/1974	Radenthein, Austria (test boring in magnesite mine)		15 (49)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
11/1974-2/1975	Innsbruck, Austria	Dolomite limestone approx. 1,224 (120) 17,000	520 (1,706)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
17-26 March 1975	Feldkirch, Austria	Limestone, approx. 1,780 (175) 25,000	112 (367)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
8-9/1975	Balmholz, Thun, Switzerland	Limestone 3,060 (300) 44,000	50 (164)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
(Mini-3) 5/1976	Penarroya, France	Sandstone 1,120-1,330 (110-130) 16,000-19,000	190 (623)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
6/1976	Aarburg, Switzerland	Limestone, marl 612-816 (60-80) 8,704-1,200 200-400 (20-40) 2,800-5,700	64 (210)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
12/1976	Kiruna, Sweden	Test bore in magnetite ore	27 (89)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
1/1977	Trondheim, Norway		120 (394)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
6/1977	Lausen, Switzerland	Limestone 1,000-1,300 (100-130) 14,800-19,000	251 (823)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
5/1978	Skoumksa, Norway		629 (2,062)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
(Mini-4) 1/1976	Inclined shaft of 30°. Duge Power Station, Norway (test bore)	Granite, gneiss		1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
3/1976	Round Hill, England	Sandstone 306-510 (30-50) 4,300-7,200	376 (1,240)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
1/1977	Trieste, Italy	Sandy limestone 2,550 (250) 36,000	170 (558)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
6/1977	Trenlo II, Italy	Dolomite, sandstone	738 (2,420)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
9/1977-2/1979	Simssee, Germany	Very soft sandstone 150-300 (15-30) 2,115-4,350	948 (3,110)					

Hard-rock Tunnelling Machines

Atlas Copco Maschinen AG. Medium to hard-rock circular and rectangular full-face and mini machines — continued

Model type and year	Project location	Rock strength kg/cm² (MPa) lb/in²	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
(Mini-5) 6/1976-9/1977	Engadine, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	3,018 (10,190)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
12/1977- 3/1978	Bonnet Bay, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	511 (1,675)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
8/1978	Engadine, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	1,229 (4,030)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
11/1979	Deep Creek, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	1,349 (4,422)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
(Mini-6) 12/1975- 1/1976	Beaver project, Montreal, Canada	Shale 700-1,500 (70-150) 10,150-21,750	152 (498)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
(Mini-6) 2/1977	Fitzpatrick, Montreal, Canada	Shale 700-1,500 (70-150) 10,150-21,750	135 (442)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
11/1979	Pewanhee, Canada		45 (147)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
(Mini-7) 1977	Tusco, U.S.A.		537 (1,760)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
1979	Columbia, U.S.A.		114 (373)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
12/1979	St. Louis, U.S.A.		140 (459)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
(Mini-8) 4/1978	Schwarzenburg, Switzerland	Sandstone 300-500 (30-50) 4,350-7,250	145 (475)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
6/1978	Bremgarten, Switzerland	Sandstone	351 (1,150)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
11/1978	Chinon I, France		176 (577)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
11/1978	Chinon II, France		178 (583)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
11/1978	Chinon III, France		175 (573)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
1/1979	Isla Bella, Italy		120 (393)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
5/1979	Sonceboz, Switzerland	Tufa, limestone	331 (1,085)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
11/1979	Lausanne, Switzerland	Limestone	120 (393)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
(Mini-9) 9/1978	Pennant Hills, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	1,079 (3,540)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
5/1979	Hornsby Heights, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700	Section I 1,301 (4,265)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		

Hard-rock Tunnelling Machines

Atlas Copco Maschinen AG. Medium to hard-rock circular and rectangular full-face and mini machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
12/1979/1980	Hornsby Heights, Sydney, Australia	Sandstone 408-612 (40-60) 5,800-8,700 (total length of project 8,000 m)	Section II 650 (2,131)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
(Mini-10) 1979	Balmholz, Switzerland Roller bit test	Limestone 3,060 (300) 44,000	100 (1,450)	1.50 × 2.40 (4 11 × 7 10½)		Not applicable		
MIDI FF 2131								
(Midi-1) 8/1978	Buffalo, U.S.A.	Limestone with intrusions of chalk 400 (40) 5,700	452 (1,481)	2.15 × 3.30 (7 1 × 10 10)				
(Midi-2) 1978	St. Etienne, France		181 (593)	2.15 × 3.30 (7 1 × 10 10)		Not applicable		

Bade & Co. GmbH (now Bade & Theelen GmbH) Rock Machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN m	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
SVM-33-RM 1956/57	Potash mine, Hangsen, Hanover			3.30 (10 10)	210 (282)	81,000 (179,000) 794		Cutters and breakers 28 (27.5)
SVM-40-RM 1961	Coal-mine, Essen			4.0 (13 1½)	550 (737)	457,000 (1,008,800) 4,482		Gear-tooth type rock bit rollers 105 (103)

Calweld (Division of Smith International Pty. Ltd.) Soft ground, medium and hard-rock tunnelling machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa)	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
TBM-1 2/1962	Chicago sewer, Kenny, Gibson, Roberts, Drummond & Bronneck	Clay, gravel, boulders, sands	1,680 (5,500)	2.29 (7 6)	22.4 (30)	54,400 (120,000) 534	6,290 (45,500) 62	Spade 9.07 (8.93)
TBM-2 2/1962	Storm drain, Fulton	Caliche	2,070 (6,800)	2.13 (7 0)	29.8 (40)	54,400 (120,000) 534	6,290 (45,500) 62	Spade 10.7 (10.5)
TBM-3 4/1963	Chicago sewer, Healy	Clay, gravel, boulders, sands, water	5,490 (18,000)	2.74 (9 0)	112 (150)	160,000 (353,000) 1,569	6,290 (45,500) 62	Spade and ripper 20.4 (20.1)
TBM-4 2/1964	Chicago sewer, Kenny	Clay, gravel, boulders, sands, water	3,660 (12,000)	2.74 (9 0)	74.6 (100)	224,000 (494,000) 2,197	8,750 (63,000) 86	Spade and ripper
TBM-5 1/1964	Chicago sewer, Healy	Clay, gravel, boulders, sands, water	2,440 (8,000)	5.79 (19 0)	224 (300)	256,000 (565,000) 2,511	68,600 (496,000) 673	Spade 65.7 (64.7)

[a] American ton = 2,000 lb

Calweld. Soft ground, medium and hard-rock tunnelling machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
TBM-6 9/1964	Chicago sewer, Healy	Clay, gravel, boulders, sands, water	1,580 (5,200)	7.92 (26 0)	224 (300)	256,000 (565,000) 2,511	68,600 (496,000) 673	Spade 65.7 (64.7)
TBM-7 7/1964	Toledo, Peirce	Sticky clay	1,830 (6,000)	2.13 (7 0)	351 (470)	160,000 (353,000) 1,569	6,360 (46,000) 62	Spade and ripper 13.6 (13.4)
TBM-8 8/1964	Cleveland, Kassouf	Soft blue clay, shale	2,130 (7,000)	2.57 (8-5)	351 (470)	192,000 (424,000) 1,883	6,290 (45,500) 62	Spade 18.2 (17.9)
TBM-9 8/1964	Chicago, Kenny	Sandy clay	3,050 (10,000)	3.45 (11 4)	112 (150)	320,000 (706,000) 3,138	12,600 (90,900) 124	Spade 40.8 (40.2)
TBM-10 1/1965	Texas, Gibraltar Co.	Soft clay, sands, unstable	1,050 (3,460)	4.95 (16 3)	112 (150)	385,000 (848,000) 3,776	20,600 (148,800) 202	Spade 27.2 (26.8)
TBM-11 10/1965	Chicago, Kenny	Clay, gravel, boulders, sands, water	2,010 (6,600)	3.45 (11 4)	224 (300)	449,000 (989,000) 4,403	36,500 (264,000) 358	Spade 60.8 (59.8)
TBM-12 1/1966	Munich subway, Wayss & Freytag	Limestone, chert, alluvium	1,830 (6,000)	6.71 (22 0)	373 (500)	2,070,000 (4,560,000) 20,300	68,600 (496,000) 673	Spade 61.3 (60.3)
TBM-13 3/1966	Portsmouth, Streeters Ltd.	Silty, sands, clay	2,290 (7,500)	3.12 (10 3)	209 (280)	320,000 (706,000) 3,138	17,100 (124,000) 168	Spade 43.1 (42.4)
TBM-14 4/1966	Japan Water Supply, Hazama-Gumi	Sandstone, hard clay	7,240 (23,760)	3.84 (12 7)	298 (400)	224,000 (494,000) 2,197	36,500 (264,000) 358	Spade and ripper 79.3 (78.1)
TBM-15 5/1966	Coventry sewer, Streeters Ltd.	Red sandstone	3,050 (10,000)	3.45 (11 4)	298 (400)	224,000 (494,000) 2,197	36,500 (264,000) 358	Disc 60.8 (59.8)
TBM-16 7/1966	Chatham sewer, Arnold & Nathan	Chalk with layers of flint	n.a.	2.13 (7 0)	149 (200)	192,000 (424,000) 1,883	11,300 (82,000) 111	Spade 25.0 (24.6)
TBM-17 6/1966	Minneapolis storm drain, American Structures	Sandstone	2,040 (6,700)	4.88 (16 0)	298 (400)	445,000 (982,000) 4,364	36,500 (264,000) 358	Disc 73,5 (72.3)
TBM-18 8/1966	Anaheim storm drain, Baker-Anderson, Solum	Silty clay, water, sand	3,050 (10,000)	2.95 (9 8)	149 (200)	320,000 (706,000) 3,138	47,400 (343,000) 465	Oscillator S-type 21.7 (21.4)
TBM-19 1/1967	Newhall tunnel, California State water project	Sandstone, siltstone, mudstone	5,470 (17,950)	7.80 (25 7)	597 (800)	3,420,000 (7,536,000) 33,540	110,000 (793,000) 1,079	Spade and disc 109 (107)
TBM-20 12/1966	Pleasant Hills	Sandy clay, sandstone	2,740 (9,000)	4.06 (13 4)	298 (400)	314,000 (692,000) 3,079	36,500 (264,000) 358	Spade and disc 50.0 (49.1)
TBM-21 2/1967	Lompoc missile site	Sandstone		3.05 (10 0)	187 (250)	156,000 (343,000) 1,530	6,290 (45,500) 62	Spade 31.8 (31.3)
TBM-22 4/1967	Munich subway, Zueblin-Hochtief	Limestone, chert, flint	2,740 (9,000)	6.86 (22 6)	373 (500)	572,000 (1,260,000) 5,610	68,600 (496,000) 673	Spade and ripper 67.2 (66.1)
TBM-23 6/1967	Montreal storm drain, Spino Con.	Glacial till, clay, sands, gravel	2,210 (7,250)	2.44 (8 0)	244 (300)	256,000 (564,000) 2,511	47,400 (343,000) 465	Oscillator diamond 30.4 (29.9)

[a] American ton = 2,000 lb

Calweld. Soft ground, medium and hard-rock tunnelling machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
TBM-24 8/1967	Sewer lines, Mitchell Bros.	Chalk	2,260 (7,400)	3.45 (11 4)	298 (400)	352,000 (777,000) 3,452	36,500 (264,000) 358	Spade 45.3 (44.6)
TBM-25 12/1967	San Francisco subway	Flowing watery sand	2,130 (7,000)	5.49 (18 0)	783 (1,050)	2,720,000 (6,000,000) 26,675	597,000 (4,320,000) 5,854	Oscillator diamond 136 (134)
TBM-26 6/1967	Milwaukee, Grange Con.	Running material, glacial till	1,370 (4,500)	3.20 (10 6)	223 (300)	753,000 (1,659,000) 7,385	89,100 (644,000) 874	Oscillator sq. bar 34.0 (33.5)
TBM-33 4/1969	Rome subway, S.A.C.O.P.	Tuff clay, mudstone, gravel, marl, hard silt	4,420 (14,500)	6.15 (20 2)	522 (700)	1,140,000 (2,512,000) 11,180	68,600 (496,000) 673	Disc, spade and ripper 114 (112)
TBM-34 4/1969	Rome subway, S.A.C.O.P.	Tuff clay, mudstone, gravel, marl, hard silt	4,420 (14,500)	6.15 (20 2)	522 (700)	1,140,000 (2,512,000) 11,180	68,600 (496,000) 673	Disc, spade and ripper 114 (112)
TBM-35 7/1968	Munich subway, Gruen & Bilfinger	Marl, limestone, flint, alluvium	1,280 (4,200)	7.75 (25 5½)	671 (900)	5,650,000 (12,452,000) 55,410	196,000 (1,420,000) 1,922	Oscillator diamond 135 (133)
TBM-36 5/1968	Calumet sewer, Kiewit	Clay, gravel, rocks	7,620 (25,000)	2.59 (8 6)	250 (335)	1,200,000 (2,656,000) 11,768	24,200 (175,000) 237	Spade 38.5 (37.9)
TBM-37 6/1968	Calumet sewer, American Structures, Kiewit	Clay, gravel, rocks	3,050 (10,000)	2.69 (8 10)	224 (300)	422,000 (930,000) 4,139	27,700 (200,000) 272	Oscillator S-type 38.5 (37.9)
TBM-39 8/1968	Edmonton sewer, Edmonton City	Clay	1,220 (4,000)	2.13 (7 0)	56 (75)	28,100 (62,000) 276	4,150 (30,000) 41	Spade 9.53 (9.38)
TBM-40 10/1969	Climax mine tunnel, Climax Molybdenum	Granitic porphyry, gneiss	610 (2,000)	3.96 (13 0)	597 (800)	512,000 (1,128,000) 5,021	48,000 (347,000) 471	GT 90.7 (89.3)
TBM-41 3/1969	Sepulveda sewer tunnel, California State water project, Drummond & Bronneck	Sandstone	2,230 (7,300)	3.66 (12 0)	224 (300)	186,000 (1,800,000) 1,825	72,500 (524,000) 711	Oscillator diamond 77.1 (75.9)
TBM-42 1/1969	Edmonton sewer, Alta-West Const.	Clay, sand, gravel	1,830 (6,000)	2.84 (9 4)	224 (300)	680,000 (1,500,000) 6,669	44,300 (320,000) 434	Oscillator spade 49.9 (49.1)
TBM-43 2/1969	Tongariro water tunnel, Codelfa Cogefar	Sand, gravel conglomerate	6,000 (19,700)	4.04 (13 3)	298 (400)	953,000 (2,100,000) 9,346	55,300 (400,000) 542	Oscillator diamond 78.5 (77.3)
TBM-44 2/1969	Edmonton sewer, City of Edmonton	Clay	3,050 (10,000)	2.13 (7 0)	56 (75)	28,100 (62,000) 276	4,150 (30,000) 41	Spade 9.53 (9.38)
TBM-45 4/1969	Winnipeg sewer, Earthworm Ltd.	Sand, clay, till, conglomerate	1,520 (5,000)	2.79 (9 2)	224 (300)	680,000 (1,500,000) 6,669	44,300 (320,000) 434	Oscillator diamond 46.7 (46.0)
TBM-46 3/1969	Bunker Hill utility, Artukovich	Clay, silty sand	274 (900)	2.03 (6 8)	56 (75)	28,100 (62,000) 276	4,150 (30,000) 41	Spade 9.07 (8.93)

[a] American ton = 2,000 lb

Calweld. Soft ground, medium and hard-rock tunnelling machines — continued

Model type and year	Project location	Rock strength kg/cm² (MPa) lb/in²	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
TBM-47 5/1969	Newhall water project, California state water project, Kiewit	Sandstone, siltstone, mudstone	2,740 (9,000)	7.87 (25 10)	1,340 (1,800)	2,750,000 (6,060,000) 26,969	55,300 (4,000,000) 542	Oscillator diamond 272 (268)
TBM-48 4/1969	Chicago sewer tunnel, May Company	Clay	1,980 (6,500)	2.39 (7 10)	75 (100)	192,000 (424,000) 1,883	8,160 (59,000) 80	Spade and ripper 20.0 (19.7)
TBM-49 7/1969	Melbourne water tunnel, Melbourne & Met. Board of Works	Clay, silt, sandstone	10,060 (33,000)	3.40 (11 2)	224 (300)	748,000 (1,650,000) 7,336	72,500 (524,000) 711	Oscillator diamond 74.9 (73.7)
TBM-50 8/1969	Barcelona subway, M.Z.O.V.-CYT	Clay, sand	8,230 (27,000)	5.94 (19 6)	522 (700)	1,130,000 (2,560,000) 11,082	68,600 (496,000) 673	Spade and ripper 114 (112)
TBM-51 5/1969	Edmonton sewer, Edmonton City	Clay	4,570 (15,000)	2.13 (7 0)	56 (75)	28,100 (62,000) 276	4,150 (30,000) 41	Spade 9.53 (9.38)
TBM-52 6/1969	Munich subway, Gruen & Bilfinger	Alluvium, clay, sand, limestone	4,330 (14,200)	7.77 (25 6)	671 (900)	5,650,000 (12,452,000) 55,410	138,000 (1,000,000) 1,353	Drag ripper 136 (134)
TBM-53 11/1969	Mather 'B' mine, Cleveland Cliffs	Hematite	61 (200) Cross cuts	2.97 (9 9)	187 (250)	136,000 (300,000) 1,334	166,000 (1,200,000) 1,628	Oscillator ripper 34.0 (33.5)
TBM-55 10/1969	Lake de Smet, Wyoming, Eagle-Western	Lignite and shale	2,560 (8,400)	3.17 (10 5)	112 (150)	45,400 (100,000) 445	8,300 (60,000) 81	Spade and ripper 27.2 (26.8)
TBM-56 stock				3.66 (12 0)	224 (300)	56,200 (124,000) 551	18,000 (130,000) 177	Disc 40.8 (40.2)
TBM-57 5/1970	Corridor Constructors, Detroit sewer tunnel	Clay, silt, sand	4,450 (14,600)	5.05 (16 7)	373 (500)	1,190,000 (2,660,000) 11,670	113,000 (820,000) 1,108	Spade 90.7 (89.3)
TBM-58 5/1970	Lawrence Ave. No. 2, Reliance Underground Const. Co.	Stiff clay	2,590 (8,500)	4.04 (13 3) 2.97 (9 9)	112 (150)	56,200 (124,000) 551	8,570 (62,000) 84	Spade and ripper 27.2 (26.8)
TBM-59 4/1970	Tauranga, New Zealand, Canadian Constructors	Volcanic tuff	3,660 (12,000)	2.29 (7 6)	75 (100)	76,700 (169,000) 752	7,610 (55,000) 75	Spade and ripper 13.6 (13.4)
TBM-60 6/1970	Edmonton sewer, City of Edmonton	Clay, sand	3,050 (10,000)	4.27 (14 0)	112 (150)	448,000 (988,000) 4,394	12,900 (93,000) 127	Spade 72.5 (71.4)
TBM-63 2/1971	Upper Salt Creek, Chicago, Kenny	Sand, silt	4,880 (16,000)	2.74 (9 0)	149 (200)	399,000 (880,000) 3,913	13,100 (95,000) 128	Spade and ripper 8.61 (8.48)
TBM-64 10/1971	AMAX Coal Co., Ayrshire Coal — 17° incline, McGuire Shaft and Tun. Corp.	Limestone, sandstone, shale	914 (3,000)	5.18 (17 0)	522 (700)	544,000 (1,200,000) 5,335	144,000 (1,044,000) 1,412	Discs 74.9 (73.7)

[a] American ton = 2,000 lb

Calweld. Soft ground, medium and hard-rock tunnelling machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
TBM-65 4/1972	Madrid subway, Pacifico-Oporto. F.O.C.-S.I.C.O.P.	Stiff clay, penuela blackish gray clay, gypsum or soft dolemite	5,110 (16,750)	8.48 (27 10)	746 (1,000)	6,420,000 (10,176,000) 62,961	144,000 (1,044,000) 1,412	Discs 364 (358)
TBM-66 5/1972	Eastern Suburbs R.R. Sydney, Australia. Codelfa Construction	Sandstone and basalt	3,960 (13,000)	5.08 (16 8)	597 (800)	544,000 (1,200,000) 5,335	72,200 (522,000) 708	Discs 140 (138)
TBM-69 8/1972	San Donato section Rome-Florence R.R. Vianini	Shale, sandstone, marl, limestone	11,000 (36,150)	11.20 $(36\ 8^3/_{16})$	1,490 (2,000)	6,530,000 (14,400,000) 64,040	415,000 (3,000,000) 4,070	Kerf 725 (714)
TBM-70 9/1972	Tonner tunnels, J. F. Shea Co. Inc.	Sandstone, shale, limestone, siltstone	6,960 (22,850)	3 43 (11 3)	298 (400)	6,530,000 (14,400,000) 64,040	41,500 (300,000) 407	Kerf 61.3 (60.3)
TBM-71 11/1972	Crosstown Interceptor sewer, Austin, Texas, Peter Kiewit Sons	Shale, limestone	9,200 (30,200)	3.20 (10 6)	298 (400)	6,530,000 (14,400,000) 64,040	41,500 (300,000) 407	Kerf 58.9 (58.0)

[a] American ton = 2,000 lb

Mannesman Demag AG (Formerly Demag Aktiengesellschaft, Germany) Medium to hard-rock machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN m	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
21H 1966 (1)	Sewerage tunnel, Dortmund	Green Sandstone 300-800 (29-78) 4,300-11,000	2,800 (9,190)	2.10 (6 11)	110 (147)	100,000 (220,000) 981		18-23 ring-tooth rollers 40 (39.4)
20-23H 1967 (2)	Water mains, Lake Constance-Stuttgart Veringendorf	Jurassic limestone to 2000 (196) 28,000	3,135 (10,300)	2.14 (7 0)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	18-23 deposit-weld discs 55 (54.1)
20-23H 1970 (2)	Freshwater tunnel, Stuttgart	Siltstone and sandstone 800-1,500 (78-147) 11,000-21,000	2,400 (7,870)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	18-23 deposit-weld discs 55 (54.1)
20-23H 1972 (2)	Freshwater tunnel, Stuttgart	Marl and siltstone 400-600 (39-59) 5,700-8,500	300 984)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	16-18 discs with TC buttons
20-23H 1972 (2)	Sewage tunnel, Trondheim, Norway	Greenstone and schist 1,500-2,000 (147-196) 21,000-28,000	4,500 (14,800)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	7-10 cutters with/without T.C. buttons 55 (54)

[a] American ton = 2,000 lb

Mannesmen Demag AG. Medium to hard-rock machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN m	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
20-23/24H 1973 (2)	Sewage tunnel, Waiblingen	Keuper marl 50-600 (5-59) 700-8,500 Shell limestone 1,500 (147) 21,000	1,000 (3,281)	2.40 (7 10)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	8-11 cutters with/without T.C. buttons
20-23H 1977 (2)	Water tunnel, Harz	Silicious slate, granite, diabase 500-2,000 (49-196) 7,000-28,000	47,000 (15,419)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	8-11 cutters with/without T.C. buttons
20-23H 1968 (3)	Sewerage tunnel, Ramscheid	Greywacke schist 800-1,200 (78-118) 1,100-1,700	300 (984)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	18-23 deposit-weld discs 55 (54.1)
20-23H 1968 (3)	Sewerage tunnel, Wuppertal	Greywacke and schist 2,940 (288) 42,000	990 (3,250)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	18-23 discs with T.C. buttons 55 (54.1)
20-12H 1968 (3)	Experimental gallery, Drensteinfurt	Marl 600 (59) 8,500	200 (656)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	18-23 discs with T.C. buttons 55 (54.1)
20-23H 1970 (3)	Outfall tunnel, Dortmund	Green Sandstone 300-800 (29-78) 4,300-11,000	460 (1,510)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	18-23 discs with T.C. buttons 55 (54.1)
20-23H 1971 (3)	Sewer tunnel, Kohlfurt	Schist, limestone and sandstone 200-1,400 (20-137) 2,800-20,000	1,400 (4,590)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	7-10 discs with T.C. buttons
20-23H 1973 (3)	Sewage tunnel, Dortmund	Green Sandstone 300-800 (30-78) 4,300-11,000	800 (2,624)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	8-11 cutters with/without T.C. buttons
20-23H 1975 (3)	Sewage tunnel, Dortmund	Green Sandstone 300-800 (30-78) 4,300-11,000	800 (2,625)	2.40 (7 10)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	8-11 cutters with/without T.C. buttons 55 (54)
20-23H 1975 (3)	Sewage tunnel, Dortmund	Green Sandstone 300-800 (30-78) 4,300-11,000	600 (1,969)	2.40 (7 10)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	8-11 cutters with/without T.C. buttons 55 (54)
28-31H 1968 (4)	Connection Oker-Grane dams, Harz	Schist and sandstone 1,200-2,500 (118-245) 17,000-36,000	6,187 (20,300)	3.15 (10 4)	375 (503)	250,000 (551,000) 2,452	22,400 (162,000) 220	18-23 discs with T.C. buttons 115 (113)
28-31H 1971 (4)	Sewer tunnel, Heiligenhaus	Siltstone and limestone 850-1,400 (83-137) 12,000-20,000	800 (2,630)	2.85 (9 4)	375 (503)	250,000 (551,000) 2,452	22,400 (162,000) 220	8-14 discs with T.C. buttons 105 (103)

[a] American ton = 2,000 lb

Mannesmen Demag AG. Medium to hard-rock machines — continued

Model type and year	Project location	Rock strength kg/cm² (MPa) lb/in²	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN m	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
28-31H 1974 (4)	Sewage tunnel, Büsnau	Sandstone 700-1,000 (69-198) 10,000-14,000 Slipstone 250-500 (25-49) 3,600-7,000	2,800 (9,186)	2.80 (9 2)	375 (503)	250,000 (551,000) 2,452	22,400 (162,000) 220	11-17 cutters with/without T.C. buttons 90 (89)
28-31H 1978 (4)	Water tunnel, Wuppertal-Barmen	Sandstone, siltstone 3,000 (294) 43,000	3,200 (10,500)	3.15 (10 4)	375 (503)	250,000 (551,000) 2,452	22,400 (16,100) 220	11-17 cutters with/without T.C. buttons 90 (89)
20-23/24H 1968 (5)	Water tunnel, Loch Lomond, Scotland	Whinstone, schist, limestone, quartz 300-3,000 (29-294) 4,300-43,000	1,200 (3,940)	2.40 (7 10)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	18-23 discs with T.C. buttons 55 (54.1)
20-23/24H 1978 (5)	Water tunnel, NaBfeld	Gneis	6,100 (20,013)	2.30 (7 7)	220 (295)	120,000 (265,000) 1,177	22,400 (162,000) 220	18-23 discs with T.C. buttons 55 (54.1)
20-23H 1969 (6)	Sewer tunnel, Stockholm, Sweden	Granite 3,000-4,000 (294-392) 43,000-57,000	2,200 (7,220)	2.30 (7 7)	220 (295)	160,000 (353,000) 1,569	22,400 (162,000) 220	18-23 discs with T.C. buttons 55 (54.1)
20-23H 1971 (6)	Freshwater tunnel, Brac, Yugoslavia	Limestone dolomite 1,200-1,400 (118-137) 17,000-20,000	8,600 (28,200)	2.30 (7 7)	220 (295)	160,000 (353,000) 1,569	22,400 (162,000) 220	7-10 discs with T.C. buttons
20-23H 1978 (6)	Böckstein	1,000-1,600 (98-157) 1,400-22,700	930 (3,051)	2.15 (7 0)	220 (295)	160,000 (353,000) 1,569	22,400 (162,000) [illegible]0	Discs with T.C. buttons 55 (54.1)
24-27H 1970 (7)	Freshwater tunnel, Erzgebirge, Czechoslovakia	Gneiss 1,000-2,500 (98-245) 14,000-36,000	6,300 (20,700)	2.67 (8 9)	285 (382)	200,000 (441,000) 1,961	22,400 (162,000) 220	8-14 discs with T.C. buttons 77 (85.8)
24-27H 1973 (7)	Freshwater tunnel, Rusova II, Czechoslovakia	Gneiss 1,000-2,500 (98-245) 14,000-36,000	3,100 (10,171)	2.67 (8 9)	285 (382)	200,000 (441,000) 1,961	22,400 (162,000) 220	11-15 cutters with/without T.C. buttons 80 (79)
24-27H 1975 (7)	Freshwater tunnel, Karlsbad, Czechoslovakia	Granite 1,500-2,500 (147-245) 21,000-36,000	1,290 (4,232)	2.67 (8 9)	285 (382)	200,000 (441,000) 1,961	22,400 (162,000) 220	11-15 cutters with/without T.C. buttons 80 (79)
24-27H 1975 (7)	Teplice, Czechoslovakia	Sandstone	1,100 (3,609)	2.67 (8 9)	285 (382)	200,000 (441,000) 1,961	22,400 (162,000) 220	11-15 cutters with/without T.C. buttons 80 (79)
24-27/30H 1972 (8)	Sewer tunnel, Durban, South Africa	Schist and sandstone 1,000-1,800 (98-177) 14,000-26,000	2,050 (6,730)	3.10 (10 2)	285 (382)	200,000 (441,000) 1,961	2,240 (162,000) 220	16 discs with T.C. buttons 82 (80.7)
24-27/30H 1977 (8)	Freshwater tunnel, Damascus, Syria	Limestone marly limestone 500-1,500 (49-147) 7,000-20,000	6,000 (19,685)	2.93 (9 7)	285 (382)	200,000 (441,000) 1,961	2,240 (162,000) 220	11-15 cutters with/without T.C. buttons 80 (79)

[a] American ton = 2,000 lb

Mannesmen Demag AG. Medium to hard-rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN m	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
34-38H 1973 (9)	Headrace tunnel, Albula, Switzerland	Limestone and schist 900-1,700 (88-167) 13,000-24,000	4,500 (14,800)	3.80 (12 6)	440 (590)	320,000 (705,000) 3,138	47,900 (346,000) 470	12-19 cutters with/without T.C. buttons 125 (123)
34-38H 1978 (9)	Pilot tunnel, Blaubeuren	1,500 (147) 20,000	2 × 270 (2 × 885)	3.80 (12 6)	440 (590)	320,000 (705,000) 3,138	47,900 (346,000) 470	12-19 cutters with/without T.C. buttons 125 (123)
24-27H 1973 (10)	Sewage tunnel, Halifax, Canada	Greywacke	1,000 (3,281)	2.42 (7 11)	285 (382)	200,000 (441,000) 1,961	22,400 (162,000) 220	11-15 cutters with/without T.C. buttons 125 (123)
24-27H 1978 (10)	Headrace tunnel, Böckstein		4,200	2.70 (8 10)	285 (382)	200,000 (441,000) 1,961	22,400 (162,000) 220	11-15 cutters with/without T.C. buttons 125 (123)
24-27H 1977 (10)	Cable tunnel Prague, Czechoslovakia	Schist 500-1,000 (49-98) 7,000-14,000 Quarzite 2,000 (196) 28,000	700 (2,296) bored so far	2.67 (8 9)	285 (382)	200,000 (441,000) 1,961	22,400 (162,000) 220	11-15 cutters with/without T.C. buttons 125 (123)
38/42HS 1973 (11)	Inclined shaft (70%) headrace tunnel, Mapragg, Switzerland	Limestone 800-1,300 (78-127) 11,000-18,000	1,400 (4,600)	4.20 (13 9)	440 (590)	320,000 (705,000) 3,138	47,900 (346,000) 470	17-25 cutters with/without T.C. buttons 150 (148)
54-58/60H 1973 (12)	Pilot heading, B.A.G. Niederrhein	Schist, sandy-shale, sandstone 400-1,600 (39-157) 5,700-23,000	2,640 (8,700)	6.00 (19 8)	880 (1,180)	640,000 (1,410,000) 6,276	112,000 (809,800) 1,100	18-34 cutters with/without T.C. buttons 300 (295)
54-58/60H 1974 (12)	Pilot heading, 1-0N B.A.G., Niederrhein	Schist, sandy shale, sand-sandstone 400-1,600 (39-157) 5,700-23,000	2,890 (9,482)	6.00 (19 8)	880 (1,180)	640,000 (1,410,000) 6,276	112,000 (809,800) 1,100	18-34 cutters with/without T.C. buttons 300 (295)
54-58/60H 1977 (12)	B.A.G., Niederrhein	Schist, sandy shale and sandstone 400-1,600 (39-157) 5,700-23,000	2,000 (6,561)	6.00 (19 8)	880 (1,180)	640,000 (1,410,000) 6,276	112,000 (809,800) 1,100	18-34 cutters with/without T.C. buttons 300 (295)
54-58/60H 1979 (12)	B.A.G., Niederrhein	Schist, sandy shale and sandstone 400-1,600 (39-157) 5,700-23,000	1,700 (5,577)	6.00 (19 8)	880 (1,180)	640,000 (1,410,000) 6,276	112,000 (809,800) 1,100	18-34 cutters with/without T.C. buttons 300 (295)
36HS 1975 (13)	Pilot heading, Dawdon, England	Schist, sandy shale 600 (59) 8,500	1,000 (281)	3.65 (12 0)	440 (590)	320,000 (705,000) 3,138	47,900 (346,000) 470	18-22 cutters with/without T.C. buttons 85 (84)

[a] American ton = 2,000 lb

Mannesmen Demag AG. Medium to hard-rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN m	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
34-38H 1975 (14)	Freshwater tunnel, Kielder, England	Sandstone, limestone, marl 2,000 (196) 28,000	12,000 (39,370)	3.50 (11 6)	440 (590)	320,000 (705,000) 3,138	33,600 (243,000) 330	12-19 cutters with/without T.C. buttons 130 (128)
34-38H 1977 (14)	Cable tunnel, Prague, Czechoslovakia	Schist 500-1,000 (49-98) 7,000-14,000 Quartzite 2,000 (196) 28,000	10,000 (32,808)	3.50 (11 6)	440 (590)	320,000 (705,000) 3,138	33,600 (243,000) 330	12-19 cutters with/without T.C. buttons 130 (128)
34-38H 1975 (15)	Freshwater tunnel, Kielder, England	Sandstone, limestone, 2,000 (196) 28,000 Dolorite 4,500 (441) 64,000	7,000 (22,966)	3.50 (11 6)	440 (590)	320,000 (705,000) 3,138	33,600 (243,000) 330	12-19 cutters with/without T.C. buttons 130 (128)
54-58/60H 1976 (16)	Pilot heading, B.A.G., Niederrhein	Schist, sandy shale and sandstone 400-1,600 (39-157) 5,700-23,000	2,720 (8,924)	6.00 (19 8)	880 (1,180)	640,000 (1,410,000) 6,276	112,000 (810,000) 1,100	18-34 cutters with/without T.C. buttons 300 (295)
54-58/61H 1977 (17)	Pilot heading, B.A.G., Dortmund	Schist, sandy shale and sandstone 400-1,600 (39-157) 5,700-23,000	7,000 (22,966)	6.10 (20 00)	880 (1,180)	640,000 (1,410,000) 6,276	112,000 (810,000) 1,100	19-34 cutters with/without T.C. buttons 300 (295)
54-58/60H 1979 (17)	Pilot heading, B.A.G., Westfalen A.R.G.E., Victoria	Schist, sandy shale and sandstone 400-1,600 (39-157) 5,700-23,000	1,600 (5,249)	6.10 (20 00)	880 (1,180)	640,000 (1,410,000) 6,276	112,000 (810,000) 1,100	19-34 cutters with/without T.C. buttons 300 (295)
24-27H 1978 (18)	Water tunnel, Kühtai	Gneiss	5,000 (16,404)	2.70 (8 10)	285 (382)	200,000 (441,000) 1,961	22,400 (162,000) 220	11-15 cutters with/without T.C. buttons
45H 1979 (19)	Coal formations, Petrosani	Sandstone, sandy shale, schist	10,000 (32,808)	4.80 (15 9)	525 (708)	500,000 (1,100,000) 4,903	83,000 (600,000) 814	24-28 cutters with/without T.C. buttons
55H 1979 (20)	Pilot heading, coal formations, Saarbergwerke	Schist, sandstone and sandy shale 400-1,600 (39-157) 5,700-23,000	10,000 (32,808)	6.00 (19 8)	640 (858)	640,000 (1,410,000) 6,276	125,000 (904,000) 1,226	30-34 discs with/without T.C. buttons

[a] American ton = 2,000 lb

Dresser Industries Hard Rock Machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) psi	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
205 5/1971	Navajo Irrigation Project Tunnel No. 3	70-420 (7-41) Sandstone, shale 1000-6000	4,800 (15,800)	6.25 (20 6)	537 (720)	718,000 (1,583,400) 7,041	146,000 (1,054,620) 1,432	36 double disc cutters (Dresser) and 32 conical picks (Kennamet) 245 (270)

[a] American ton = 2,000 lb

Dresser Industries Hard Rock Machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) psi	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
205	Navajo Irrigation Project Tunnel No. 3A	70-420 (7-41) Sandstone, shale 1000-6000	1,043 (3,423)	6.25 (20 6)	537 (720)	718,000 (1,583,400) 7,041	146,000 (1,054,620) 1,432	36 double disc cutters (Dresser) and 32 conical picks (Kennamet) 245 (270)

[a] American ton = 2,000 lb

Greenside/McAlpine T.B.M.s

Model Type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Tunnel diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
Single head 1968	Hinkley Nuclear Power Station	Limestone/ mudstone 780-2,360 (76-230) 11,000-34,000	1,100 (3,600)	3.1-4.1 (10 2-13 5½)	138 (185)	12,200 (27,000) (119) for sumping		Two-edged picks (tungsten carbide tipped)
1969	Hunterston Nuclear Power Station	Sandstone 640-1,100 (63-108) 9,100-15,600	850 (2,800)	3.6-4.0 (11 9½-13 1)	138 (185)			Two-edged picks (tungsten carbide tipped)
1970	St. Maximin, Provence	Limestone 1,280-1,430 (126-140) 18,200-20,300	1,100 (3,600)	4.1-4.7 (13 5½-15 5)	138 (185)			Two-edged picks (tungsten carbide tipped)
Double head 1970	St. Maximin, Provence	Limestone 1,280-1,430 (126-140) 18,200-20,300		4.1-4.7 (13 5½-15 5)	224 (300)			Two-edged picks (tungsten carbide tipped)
1970	Severn-Wye cable tunnel	Limestone/ sandstone 1,400-2,500 (137-245) 19,900-35,600	1,815 (5,950)	3.5 (11 6)	224 (300)		4,180 (30,000) 41 on the drum 17,538 (127,000) 172 on the arm	Two-edged picks (tungsten carbide tipped)

Habegger Limited Rock machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
836 1966	Pilot railway, tunnel, Japan	352-2,390 (35-234) Tuff, andesite 5,000-34,000	20,100 (66,000)	3.51 (11 6)	485 (650)	234,000 (515,000) 2,295	69,200 (500,000) 679	Picks 86.3 (85)
836 1967	Hydroelectric, Chur, Switzerland	984-1,480 (97-145) Shale, quartz, limestone 14,000-21,000	5,790 (19,000)	3.51 (11 6)	485 (650)	234,000 (515,000) 2,295	69,200 (500,000) 679	Picks 86.3 (85)
829 1967	Water tunnel, Stuttgart, Germany			2.90 (9 6)	410 (550)			Picks 66 (65)
836 1968	Pilot rail tunnel, Japan			3.51 (11 6)	485 (650)	234,000 (515,000) 2,295	69,200 (500,000) 679	Picks 86.3 (85)
840 1968	Pilot rail tunnel, Japan			4.04 (13 3)				

Hughes Tool Company Medium and hard-rock machines

Model type and year	Project location	Rock strength kg/cm² (MPa) lb/in²	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
40 in 1958	Hugh B. Williams Various Texas stone quarries	Chalk, sandstone, limestone, granite 176, 1,480, 1,550 and 2,110 (17, 145, 152 and 207) 2,500, 21,000, 22,000, 30,000	Approx. 3,230 (10,600)	1.01 (3 4)	78.3 (105)	36,200 (80,000) 355 40,800 (90,000) 400 77,100 (170,100) 756	3,312 (24,000) 32	9 milled tooth rollers and carbide rollers
1959	National Coal Board, England	Chalk, sandstone, limestone, granite 176, 1,480, 1,500 and 2,110 (17, 145, 152 and 207) 2,500, 21,000, 22,000, 30,000	Approx. 3,230 (10,600)	1.01 (3 4)	78.3 (105)	36,200 (80,000) 355 40,800 (90,000) 400 77,100 (170,100) 756	3,312 (24,000) 32	9 milled tooth rollers and carbide rollers
1960	American Gilsonite Co., Utah	Chalk, sandstone, limestone, granite 176, 1,480, 1,5[illegible] and 2,110 (17, 145, 152 and 207) 2,500, 21,000, 22,000, 30,000	Approx. 3,230 (10,600)	1.01 (3 4)	78.3 (105)	36,200 (80,000) 355 40,800 (90,000) 400 77,100 (170,100) 756	3,312 (24,000) 32	9 milled tooth rollers and carbide rollers
40 in Mod. to 54 in 1961-64	American Gilsonite Co., Utah	Siltstone, sandstone 352-1,480 (35-145) 5,000-21,000	Approx. 4,820 (15,800)	1.32 (4 4)	78.3 (105)	40,800 (90,000) 400	3,312 (24,000) 32	13 milled tooth rollers
100 in 1961	Peter Kiewit Sons	Shale, sandstone, limestone 141, 562 and 1,970 (14, 55 and 193) 2,000, 8,000, 28,000		2.54 (8 4)	96.0 (130)	45,400 (100,000) 445		22 milled tooth rollers and drag teeth
80 in 1963	Morrison Knudsen — Arizona, Michigan. Mogollon Rim, Wirth, West Germany	Sandstone, granite (79-101) 11,000-15,000 (79-101) 1,340-2,110 (131-207) 19,000-30,000	2,290 (7,500)	2.03 (6 8)	216 (290)	272,000 (600,000) 2,668	17,664 (128,000) 173	(Ser. 12) 24 milled tooth rollers and carbide rollers
80 in mod. to 84 in 1963	Morrison Knudsen Co., White Pine, White Pine Copper Co., Michigan	Sandstone, shale 914,844 and 1,480 (90, 83 and 145) 13,000, 12,000 and 21,000	805 (2,640)-3,230 (10,600)	2.13 (7 0)	216 (290)	83,000 (600,000) 814	17,664 (128,000) 173	(Ser. 12) 24 and 14 milled tooth rollers, carbide rollers and disc cutter
238 in to 254 in Betti I 1965	Fenix & Scisson Inc., New Mexico Navajo Irrigation	Sandstone 387-492 (38-48) 5,500-7,000	3,050 (10,600)	6.04-6.45 (19 10-21 2)	858 (1,150)	635,000 (1,400,000) 6,227	156,630 (1,135,000) 1,536	(Ser. 12 and 15) 44 milled tooth rollers and disc cutter 236 (260)
102 in	Reynolds Electrical & Engineering Co., Las Vegas			2.59 (8 6)	224 (300)	272,000 (600,000) 2,668	17,700 (128,000) 174	(Ser. 12) 21 milled tooth or carbide cutters

[a] American ton = 2,000 lb

Jarva Inc. Rock machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
Mark 14 (101) 1308 (1) 10/1965- 5/1966	22 St. relief sewer, Philadelphia, Pa.	Mica schist hornblende 422-1,758 (41-172) 6,000-25,000	497 (1,632)	4.17 (13 8)	373 (500)	393,000 (866,000) 3,854	38,000 (275,000) 373	Carbide insert kerf 73 (80)
1006 10/1966- 4/1967 (1)	St. Louis sewer, St. Louis Metro. sewer dist.	Limestone 984-1,336 (97-131) 1,400-19,000	1,249 (4,100)	3.20 (10 6)	373 (500)	393,000 (866,000) 3,854	38,000 (275,000) 373	Carbide insert kerf 73 (80)
1300 9/1967- 9/1968 (1)	Development drift, Cleveland Cliffs Iron Company	Hematite, greywacke shale 703 (69) 10,000	325 (1,070)	3.96 (13 0)	373 (500)	393,000 (866,000) 3,854	38,000 (275,000) 373	Carbide insert kerf 73 (80)
1400 1/1970- 6/1970 (1)	16° incline shaft, Oak Park mine, Hanna Coal Div.	Sandstone, shale 492 (48) 7,000	549 (1,800)	4.27 (14 0)	373 (500)	393,000 (866,000) 3,854	38,000 (275,000) 373	Carbide insert kerf 73 (80)
Mark 8 (102) 800 6/1965- 12/1965 (2)	St. Louis sewer, St. Louis Metro. Sewer Dist.	Limestone 984-1,195 (97-117) 14,000-17,000	945 (3,100)	2.44 (8 0)	224 (300)	254,000 (560,000) 2,491	18,000 (130,000) 177	Carbide insert 27 (30)
800 1/1968- 4/1968 (2)	St. Louis sewer, St. Louis Metro. Sewer Dist.	Limestone 984-1,195 (97-117) 14,000-17,000	858 (2,814)	2.44 (8 0)	224 (300)	254,000 (560,000) 2,491	18,000 (130,000) 177	Carbide insert 27 (30)
800 3/1968- 7/1968 (2)	Sewer tunnel, Metro. Sanitary Div. of Chicago	Limestone 703-1,125 (69-110) 10,000-16,000	701 (2,300)	2.44 (8 0)	224 (300)	254,000 (560,000) 2,491	18,000 (130,000) 177	Carbide insert 27 (30)
800 8/1969- 8/1969 (2)	St. Louis sewer, St. Louis Metro. Sewer Dist.	Limestone 984-1,195 (97-117) 14,000-17,000	149 (490)	2.44 (8 0)	224 (300)	254,000 (560,000) 2,491	18,000 (130,000) 177	Carbide insert 27 (30)
1000 4/1970- 7/1970 (2)	Milwaukee sewer, Milwaukee, Sewerage Comm.	Limestone, shale 1,055 (103) 15,000	1,313 (4,309)	3.05 (10 0)	280 (375)	192,000 (424,000) 1,882	24,000 (170,000) 235	Carbide insert 41 (45)
806 6/1972- 7/1973 (2)	N. Branch Interceptor, N. Heading, N.Y.C. Dept. of Public Works	Mica, schist 1,406-2,109 (138-207) 20,000-30,000	2,705 (8,875)	2.59 (8 6)	280 (375)	312,000 (688,000) 3,059	22,000 (157,000) 215	43 (47)
900 11/1974- 2/1975 (2)	Water diversion tunnel, Alabama Power Co.	845 (83) 12,000	245 (805)	2.74 (9 0)	280 (375)	312,000 (688,000) 3,059	22,000 (157,000) 215	43 (47)
802 5/1975- 7/1975 (2)	Sanitary sewer, McCandless T'ship Sanitary Authority	Sandstone 563 (55) 8,000	195 (640)	2.49 (8 2)	280 (375)	312,000 (688,000) 3,059	22,000 (157,000) 215	43 (47)
802 2/1976- 4/1976 (2)	Water Div., Amos Power Plant, American Electric Power	Sandstone 563 (55) 8,000	198 (650)	2.44 (8 0)	280 (375)	312,00 (688,000) 3,059	22,000 (157,000) 215	43 (47)

[a] American ton = 2,000 lb

Jarva Inc. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
802 5/1976- 7/1976 (2)	Mine development drift, Grace Mine, Bethlehem Steel	Chlorite magnetite 563 (55) 8,000	183 (600)	2.49 (8 2)	280 (375)	312,000 (688,000) 3,059	22,000 (157,000) 215	43 (47)
1000 7/1978- 12 /1978 (2)	− 30% incline slope, Westmoreland Coal Co.	Shale, coal, sandstone, limestone, fireclay 845-1,680 (83-165) 12,000-165,000	319 (1,045)	3.05 (10 0)	280 (375)	312,000 (688,000) 3,059	22,000 (157,000) 215	45 (50)
1000 5/1979 (2)	+ 25% incline slope, United Pocahontas Coal Co.	Shale, sandstone, limestone 563-1,125 (55-110) 8,000-16,000	945 (3,100)	3.05 (10 0)	280 (375)	312,000 (688,000) 3,059	22,000 (157,000) 215	45 (50)
Mark 8 (103) 800 11/1965- 12/1965 (3)	St. Louis sewer, St. Louis Metro. Sewer Dist.	Limestone 984-1,195 (97-117) 14,000-17,000	272 (891)	2.44 (8 0)	223 (300)	254,000 (560,000) 2,490	18,000 (132,000) 177	27 (30)
800 4/1966- 7/1966 (3)	St. Louis sewer, St. Louis Metro. Sewer Dist.	Limestone 984-1,195 (97-117) 14,000-17,000	937 (3,075)	3.05 (10 0)	223 (300)	254,000 (560,000) 2,490	18,000 (132,000) 177	27 (30)
1000 9/1967- 12/1967 (3)	St. Louis sewer, St. Louis Metro. Sewer Dist.	984-1,336 (97-131) 14,000-19,000	1,003 (3,290)	3.05 (10 0)	223 (300)	254,000 (560,000) 2,490	18,000 (132,000) 177	32 (35)
1000 3/1968- 7/1968 (3)	St. Louis sewer, St. Louis Metro. Sewer Dist.	984-1,336 (97-131) 14,000-19,000	792 (2,598)	3.05 (10 0)	223 (300)	254,000 (560,000) 2,490	18,000 (132,000) 177	32 (35)
900 10/1968- 12/1969 (3)	Development drift, Hecla Mining Co.	Quartzite 2,109-3,023 (198-296) 30,000-43,000	152 (500)	2.74 (9 0)	223 (300)	254,000 (560,000) 2,490	18,000 (132,000) 177	32 (35)
900 11/1971- 2/1972 (3)	Sewer tunnel, City of Dunkirk, New York	Shale 211 (21) 3,000	699 (2,294)	2.74 (9 0)	179 (240)	192,000 (424,000) 1,880	12,000 (88,000) 118	32 (35)
800 7/1972- 9/1972 (3)	Utility R.R. crossing, Ohio Bell Telephone Co.	Shale 211 (21) 3,000	183 (600)	2.44 (8 0)	179 (240)	192,000 (424,000) 1,880	12,000 (88,000) 118	32 (35)
801 3/1974- 11/1974 (3)	Contract No. 2, French Creek Sanitary District	Sandstone, shale 181-984 (18-97) 4,000-14,000	975 (3,200)	2.48 (8 1½)	279 (375)	183,000 (403,000) 1,790	22,000 (159,000) 216	43 (47)
1006 9/1975- 2/1976 (3)	Milwaukee sewer tunnel, Milwaukee Sewerage Comm.	Limestone 1,055 (103) 15,000	940 (3,085)	3.05 (10 0)	279 (375)	227,000 (500,000) 2,220	22,000 (159,000) 216	50 (55)
800 8/1976- 11/1976 (3)	Sewer tunnel, Davenport, Iowa	Limestone 844-985 (83-97) 12,000-14,000	917 (3,010)	2.44 (8 0)	279 (375)	183,000 (403,000) 1,790	22,000 (159,000) 216	50 (55)

[a] American ton = 2,000 lb

Jarva Inc. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm² (MPa) lb/in²	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
907 2/1977-3/1977 (3)	Sewer tunnel, Little Blue Valley Sewer Dist.	Sandstone 703 (69) 10,000	251 (825)	2.92 (9 7)	279 (375)	183,000 (403,000) 1,790	22,000 (159,000) 216	50 (55)
907 10/1977-12/1977 (3)	Sewer tunnel, Mill Creek Interceptor	Shale 563 (55) 8,000	145 (475)	2.44 (8 0)	279 (375)	183,000 (403,000) 1,790	22,000 (159,000) 216	50 (55)
800 6/1979 (3)	Water Main W-80, Washington Suburban Sanitary Comm.	Quartz gneiss 1,055-2,460 (103-241) 15,000-35,000	1,402 (4,600)	2.44 (8 0)	279 (375)	183,000 (403,000) 1,790	22,000 (159,000) 216	50 (55)
Mark 11 (104) 1000 4/1967-11/1967 (4)	27° inclined shaft, Republic Steel Corp.	Magnetite, hornblende, biotite and grey granite gneiss 703-2,461 (69-241) 10,000-35,000	234 (768)	3.05 (10 0)	223 (300)	281,000 (620,000) 2,760	24,000 (170,000) 235	50 (55)
1200 9/1968-6/1969 (4)	River Mt. tunnel, U.S. Bureau of Reclamation	Tuffs, rhyolite, rhyodocite 70-352 210-703 281-1,617 (6.9-35 21-69 28-159) 1,000-5,000 3,000-10,000 4,000-23,000	6,096 (20,000)	3.66 (12 0)	223 (300)	281,000 (620,000) 2,760	24,000 (170,000) 235	59 (65)
1102 10/1969-3/1970 (4)	Milwaukee sewer, Milwaukee Sewerage Comm.	Limestone 1,055 (103) 15,000	1,171 (3,841)	3.40 (11 2)	223 (300)	281,000 (620,000) 2,760	24,000 (170,000) 235	59 (65)
102 1/1971-4/1971 (4)	Milwaukee Sewerage Comm.	Limestone 1,055 (103) 15,000	849 (2,784)	3.40 (11 2)	223 (300)	281,000 (620,000) 2,760	24,000 (170,000) 235	59 (65)
1102 7/1971-10/1971 (4)	Contract 817 Milwaukee Sewerage Comm.	Limestone 1,055 (103) 15,000	1,343 (4,407)	3.40 (11 2)	223 (300)	281,000 (620,000) 2,760	24,000 (170,000) 235	59 (65)
1102 12/1971-2/1972 (4)	Contract 843, Milwaukee Sewerage Comm.	Limestone 1,055 (103) 15,000	857 (2,813)	3.40 (11 2)	223 (300)	281,000 (620,000) 2,760	24,000 (170,000) 235	59 (65)
1200 5/1974-8/1974 (4)	Mill Run sewer, city of Springfield, Ohio	Dolomite 1,130 (111) 16,000	701 (2,235)	3.66 (12 0)	279 (375)	257,000 (566,000) 2,520	25,000 (183,000) 245	59 (65)
1200 8/1975-4/1976 (4)	Tijuana Aqueduct, Mexican government, Baja, Calif., Mexico	Migmatite 2,800-4,570 (275-448) 40,000-65,000	843 (2,766)	3.66 (12 0)	279 (375)	257,000 (566,000) 2,520	25,000 (183,000) 245	59 (65)
1200 9/1977-4/1978 (4)	Mine development drift, Pachuca, Mexico	Shale 563 (55) 8,000	1,530 (5,000)	3.66 (12 0)	279 (375)	257,000 (566,000) 2,520	25,000 (183,000) 245	59 (65)

[a] American ton = 2,000 lb

Jarva Inc. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
Mark 21 (105) 2000 10/1968-10/1969 (5)	Bay Area Rapid Transit System, San Francisco, Calif.	Serpentine, greenstone, chert, breccia 70-2,810 (69-276) 1,000-40,000	2,104 (6,900)	6.10 (20 0)	559 (750)	771,000 (1,700,000) 7,560	91,000 (660,000) 892	195 (215)
Mark 21 (106) 1610 6/1969-11/1970 (6)	Calumet 18E., Ext. A, Metro. Sanitary Dist. of Chicago, Ill.	Dolomite, limestone 984-2,742 (14,000-39,000) 97-269	5,424 (17,794)	5.13 (16 10)	746 (1,000)	771,000 (1,700,000) 7,560	123,000 (890,000) 1,210	195 (215)
1902 2/1976-4/1978 (6)	Section K-2, Contract 1K0011, WMATA, Washington	Quartz, gneiss 1,055-2,460 (103-241) 15,000-35,000	1,768 (5,800)	6.33 (20 9)	746 (1,000)	816,000 (1,800,000) 8,000	91,000 (660,000) 892	227 (250)
Mark 12 (107) 1100 2/1971-8/1971 (7)	Queen Lane raw water conduit, city of Philadelphia, Pa.	Mica schist, quartz 422-1,758 (42-172) 6,000-25,000	1,763 (5,784)	3.35 (11 0)	373 (500)	544,000 (1,200,000) 5,430	33,000 (240,000) 324	82 (90)
1403 5/1972-10/1972 (7)	Moss Point Drainage System, city of Euclid, Ohio	Shale 211 (21) 3,000	1,122 (3,682)	4.34 (14 3)	373 (500)	544,000 (1,200,000) 5,430	33,000 (240,000) 324	82 (90)
1302 2/1974-7/1974 (7)	Northwest Area interceptor sewer, Contract No. 3, Cleveland Sewer Dist.	Shale 281 (28) 4,000	1,478 (4,850)	4.00 (13 2)	373 (500)	544,000 (1,200,000) 5,430	33,000 (240,000) 324	82 (90)
1202 3/1975-12/1975 (7)	Northwest Area interceptor sewer, Contract No. 6, Cleveland Sewer Dist.	Shale 281 (28) 4,000	1,981 (6,500)	3.71 (12 2)	373 (500)	544,000 (1,200,000) 5,430	33,000 (240,000) 324	82 (90)
1206 11/1978-3/1979 (7)	Sanitary sewer, City of Willoughby, Ohio	Shale 280 (27) 4,000	1,524 (5,000)	3.81 (12 6)	373 (500)	544,000 (1,200,000) 5,430	33,000 (240,000) 324	82 (90)
Mark 18 (108) 480 10/1971-3/1972 (8)[b]	Sakawa river water tunnel, Tokyo, Japan	Tuffs, sandstone, conglomerate 563-1,266 (55-124) 8,000-18,000	1,000 (3,280)	4.80 (15 9)	559 (750)	850,000 (1,875,000) 8,340	73,000 (525,000) 716	204 (225)
Mark 12 (109) 1100 2/1972-3/1973 (9)	N. Branch Interceptor S. Heading, N.Y.C. Dept. of Public Works	Mica schist 1,406-2,109 (138-207) 20,000-30,000	2,863 (9,392)	3.35 (11 0)	373 (500)	544,000 (1,200,000) 5,430	33,000 (240,000) 324	82 (90)
1102 11/1973-6/1975 (9)	South Ottawa collector sewer, Phase I	Shale, limestone 210-420 (21-41) 3,000-6,000	3,977 (13,049)	3.40 (11 2)	373 (500)	544,000 (1,200,000) 5,430	33,000 (240,000) 324	82 (90)
Mark 12 (109) 1300 3/1976-3/1977 (9)	Water inlet tunnel, Municipality of Metro. Toronto	Shale 422 (41) 6,000	3,048 (10,000)	3.96 (13 0)	373 (500)	544,000 (1,200,000) 5,430	33,000 (240,000) 324	86 (95)

[a] American ton = 2,000 lb

[b] Kawasaki/Jarva

Jarva Inc. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
1300 11/1977- 5/1978 (9)	Sewer tunnel, Sayerville, Contract 33F, N.J.	Shale 563 (55) 8,000	1,280 (4,200)	3.96 (13 0)	373 (500)	544,000 (1,200,000) 5,430	33,000 (240,000) 324	86 (95)
Mark 22 (111) 2100 2/1972- 6/1976 (11)	Kaimai R.R. deviation tunnel, New Zealand Ministry of Works	Welded tuff, ignimbrite, andesite 14-1,055 (1.3-103) 200-15,000	4,780 (15,684)	6.40/5.94 (21 0/19 0)	746 (1,000)	1,000,000 (2,200,000) 9,810	128,000 (921,000)	227 (250)
Mark 24 (112) 2303 11/1974- 1/1977 (12)	Contract No. 313, Melbourne Underground Rail Loop Authority, Australia	Sandstone, siltstone, clay 7-1,756 (0.6-172) 100-25,000	5,200 (17,000)	7.10 (23 3½)	746 (1,000)	454,000 (1,000,000) 4,450	194,000 (1,400,000) 1,900	182 (200)
Mark 12 (113) 1400 9/1975- 2/1976 (13)	8% Urling No. 3 slope, R & P Coal Company, near Indiana, Pa.	Shale, coal, sandstone, limestone, fireclay 140-845 (14-83) 2,000-12,000	762 (2,500)	4.27 (14 0)	373 (500)	544,000 (1,200,000) 5,340	34,000 (244,000) 333	122 (134)
1400 9/1975- 2/1976 (13)	10% Urling No. 4 slope, R & P Coal Company, near Indiana, Pa.	Shale, coal, sandstone, limestone, fireclay 140-845 (14-83) 2,000-12,000	396 (1,300)	4.27 (14 0)	373 (500)	544,000 (1,200,000) 5,340	34,000 (244,000) 333	122 (134)
1400 9/1979 (13)	Conveyor Haulage tunnel, R & P Coal Co., near Indiana, Pa.	Shale, sandstone 563-845 (55-83) 8,000-12,000	427 (1,400)	4.27 (14 0)	373 (500)	544,000 (1,200,000) 5,340	34,000 (244,000) 333	122 (134)
Mark 12 (114) 1200 6/1975- 1/1978 (14)	Project A-206 108" water-main, City of Montreal	Limestone, shale, Gabbro intrusive 984 (97) 14,000	7,976 (26,138)	3.66 (12 0)	373 (500)	544,000 (1,200,000) 5,340	34,000 (244,000) 333	96 (106)
1206 (14)	Bi-County water tunnel, Washington Suburban Sanitary Comm., Md.	Quartz, granite, schist 1,266 (124) 18,000	5,477 (18,000)	3.8 (12 6)	373 (500)	544,000 (1,200,000) 5,340	34,000 (244,000) 333	96 (106)
Mark 30 (115) 3001 4/1977 (15)	Contract 72-049-2H Addison to Wilmette Metro. Sanitary Dist. of Greater Chicago	Limestone 984-2,742 (97-269) 14,000-39,000	8,458 (27,750)	9.17 (30 1)	1,790 (2,400)	1,361,000 (3,000,000) 13,300	436,000 (3,150,000) 4,280	454 (500)
Mark 22 (116) 2201 10/1976- 11/1978 (16)	Contract 72-049-2H, Addison to Wilmette Metro. Sanitary Dist. of Greater Chicago	Limestone 984-2,742 (97-269) 14,000-39,000	7,315 (24,000)	6.73 (22 1)	895 (1,200)	907,000 (2,000,000) 8,890	160,000 (1,156,000) 1,570	318 (350)

[a] American ton = 2,000 lb

Jarva Inc. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
Mark 10 (117) 800 12/1975- 5/1976 (17)	Snyder storm relief sewer, Contract No. 3, town of Amherst, N.Y.	Sandstone 563 (55) 8,000	1,308 (4,292)	2.44 (8 0)	279 (375)	227,000 (500,000) 2,220	22,000 (162,000) 216	50 (55)
907 12/1976- 4/1977 (17)	Cont. 1005, Sect. 1.3, Montreal Urban Community, Quebec, Canada	Limestone, shale, gabbro intrusive 984, 280, 2,040 (97, 27, 200) 14,000, 4,000, 29,000	3,350 (11,000)	2.92 (9 7)	279 (375)	227,000 (500,000) 2,220	22,000 (162,000) 216	54 (60)
Mark 12 (118) 1307 12/1976- 10/1977 (18)	Nashville Ave. sewer, Chicago Dept. of Public Works	Limestone 984-2,742 (97-269) 14,000-39,000)	3,700 (12,139)	4.14 (13 7)	447 (600)	544,000 (1,200,000) 5,340	41,000 (293,000) 402	104 (115)
1307 7/1979 (18)	Recycled mill water tunnel, Inland Steel, East Chicago	Limestone 1,125 (110) 16,000	610 (2,000)	4.14 (13 7)	447 (600)	544,000 (1,200,000) 5,340	41,000 (293,000) 402	104 (115)
Mark 6 (119) 606 5/1977- 1/1979 (19)	Sewer tunnel, Davenport, Iowa	Limestone 845-984 (83-97) 12,000-14,000	1,219 (4,000)	1.98 (6 6)	149 (200)	148,000 (325,000) 1,450	11,000 (84,000) 108	25 (27)
706 8/1979 (19)	Hales Corners interceptor sewer, Milwaukee, Wis.	Limestone 1,055 (103) 15,000	1,950 (6,400)	2.29 (7 6)	149 (200)	148,000 (325,000) 1,450	11,000 (84,000) 108	25 (27)
Mark 12 (120) 1202 3/1978 10/1978 (20)	Intake and discharge water tunnel, Perry Nuclear Power Plant, Ohio	Shale 703 (69) 10,000	1,730 (5,678)	3.19 (12 2)	373 (500)	544,000 (1,200,000) 5,340	34,000 (239,000) 333	95 (105)
1206 7/1979 (20)	Bi-County water tunnel, Washington Suburban Sanitary Comm., Rockville, Md.	Quartz, gneiss, schist 1,266 (124) 18,000	4,572 (15,000)	3.81 (12 6)	447 (600)	544,000 (1,200,000) 5,340	34,000 (239,000) 333	95 (105)
Mark 30 (121) 3203 4/1979 (21)	Contract 75-125-2H, Metro. Sanitary Dist. of Greater Chicago	Limestone 984-2,742 (97-269) 14,000-39,000	7,498 (24,600)	9.83 (32 3)	1,790 (2,400)	1,361,000 (3,000,000) 13,300	392,000 (2,833,000) 3,840	765 (850)
Mark 15 (122) 1503 3/1979 (22)	Contract 75-124-2H, Metro. Sanitary Dist. of Greater Chicago	Limestone 984-2,742 (97-269) 14,000-39,000	1,981 (6,500)	4.65 (15 3)	559 (750)	544,000 (1,200,000) 5,340	57,000 (419,000) 559	162 (180)
Mark 10T (123) 1006 1/1980 (23)	Three Rivers water quality management program, Atlanta, Ga.	Gneiss, schist, granite 914-1,547 (90-152) 13,000-22,000	8,473 (27,800)	3.20 (10 6)	335 (450)	418,000 (920,000) 4,100	26,000 (189,000) 255	64 (70)

[a] American ton = 2,000 lb

Jarva Inc. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)^a
Mark 6 (124) 606 6/1980 (24)	Lemont intercepting sewer, 1, 2, and 3 M.S.D.G.C., Chicago	Limestone 1,125 (110) 16,000	5,377 (17,640)	1.98 (6 6)	149 (200)	192,000 (422,000) 1,880	12,000 (87,000) 118	31 (35)
Mark 6 (125) 702 8/1980 (25)	Bi-County water tunnel, Washington Suburban Sanitary Comm. Rockville, Md.	Quartz, gneiss, schist 1,266 (124) 18,000	305 (1,000)	2.18 (7 2)	149 (200)	192,000 (422,000) 1,880	12,000 (87,000) 118	33 (38)

Jarva Inc. Mechanised shields and hybrid machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)^a
SM-1500 Hard-rock slot machine 1979	Mine entry — haulage system, Westmoreland Coal Co., MacAlpin mine to East Gulf mine	Bottom rock	5.6 km (3½ m)	4.57 wide (15 0) 107 cm high (42 in)	224 (300)	68,000 (150,000) 667	20,000 (147,000) 200	Disc cutters 65 (72)
S0911W Mechanized shield 4/1971-1/1972	Calumet intercept sewer, No. 17G, Chicago Metro. San. Dist., Chicago, Ill.	Clay	2,118 (6,950)	3.02 (10 0)	134 (180)	435,000 (959,000) 4,266	17,000 (123,000) 167	Trencher teeth 27 (30)
S1205W 4/1971-5/1972 Mechanized shield	Inner City relief sewer, Ft. Wayne, Ind.	Clay	1,167 (3,830)	3.79 (12 5)	112 (150)	680,000 (1,500,000) 6,669	26,000 (188,000) 255	Trencher teeth 36 (40)
S2209BJ 9/1971-12/1971 Mechanized shield	Flint River Improv. Atlanta Airport City	Clay	272 (891)	6.95 (22 9½)		2,722,000 (6,000,000) 26,690		159 (175)
S1907-BH 3/1974-10/1974 Hybrid machine	Northwest Area interceptor sewer, Contract No. 2, Cleveland Sewer Dist.	Stiff grey clay	366 (1,200)	5.97 (19 7)	Shield 45 (60) Backhoe 150 (110)	839,000 (1,840,000) 8,179		38 (42)
S1800BJ 8/1974-4/1975 Mechanized shield	Section D-4a Contract 1D0041, W.M.A.T.A., Washington D.C.	Stiff clay with traces of wet sandy silt	381 (1,250)	5.50 (18 0)	185 (250)	2,268,000 (5,000,000) 22,242		86.6 (95)
S1800BJ 1/1975-4/1975 Mechanized shield	Section D-4a Contract 1D0041, W.M.A.T.A., Washington D.C.	Stiff clay with traces of wet sandy silt	381 (1,250)	5.50 (18 0)	185 (250)	2,268,000 (5,000,000) 22,242		86.6 (95)

^{a}American ton = 2,000 lb

Jarva Inc. Mechanised shields and hybrid machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
M/F (110) S1907W 4/1972- 2/1973 (10)	Moss Point drainage system, city of Euclid	Shale, clay 141 (14) 2,000	1,335 (4,380)	5.97 (19 7)	690 (925)	2.268,000 (5,000,000) 22,200	111,000 (800,000) 1,090	Rotary discs 159 (175)
S2205W 12/1973- 10/1974 (10)	Capitol Hill relief sewer, Sect. 4, Dept. of Environmental Services	Stiff brown clay, silty clay	594 (1,948)	6.85 (22 5½)	690 (925)	2,268,000 (5,000,000) 22,200	111,000 (800,000) 1,090	182 (200)

[a] American ton = 2,000 lb

Komatsu Limited (Komatsu-Robbins) Rock Machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
TM230G 1964	Nihama tunnel and others, Japan	Rock 598-1,620 (59-159) 8,500-23,000	2,000 (6,560)	2.3 (7 7)	112 (150)	136,000 (300,000) 1,334	27,700 (87,000) 272	Discs 24.5 (27)
TM320G 1967	Matsushima mine, Japan	Rock 984 (97) 14,000	Contin.	3.2 (10 6)	298 (400)	249,000 (550,000) 2,442	79,600 (250,000) 781	Discs 69.8 (77)
TM445G 1967	Enasan tunnel, Japan	Rock 1,410 (138) 20,000	8,500 (27,900)	4.45 (14 7)	477 (640)	499,000 (1,100,000) 4,894	191,000 (600,000) 1,873	Discs 180(198)
TM430G 1967	Inuyama tunnel, Japan	Rock 1,760 (173) 25,000	1,800 (5,910)	4.3 (14 1)	477 (640)	499,000 (1,100,000) 4,894	191,000 (600,000) 1,873	Discs 120 (132)
1970	Kagawa water supply tunnel, Japan	Rock 2,110 (207) 30,000	8,000 (26,200)	4.3 (14 1)	477 (640)	499,000 (1,100,000) 4,894	191,000 (600,000) 1,873	Discs 120 (132)
TM450G 1968	Taiheizan pilot tunnel for railway	Soft shale, sandstone	800 (2,620)	4.5 (14 9)	500 (670)	499,000 (1,100,000) 4,894	191,000 (600,000) 1,873	Discs 145 (160)
TM350G 1969	Okinawa water tunnel, Japan	Rock 70.3-2,110 (7-207) 1,000-30,000	2,690 (8,820)	3.5 (11 6)	395 (530)	369,000 (814,000) 3,619	57,300 (180,000) 561	Discs 81.6 (90)
TM480G 1970	Kanagawa Pref. wide area water supply tunnel Japan	Rock 400-1,400 (39-138) 6,000-20,000	1,600 (5,250)	4.8 (15 9)	500 (670)	499,000 (1,100,000) 4,894	85,600 (270,000) 839	Discs 154 (170)
TM40G 1972	Gunma Pref. water tunnel, Japan	984-2,110 (97-207) 14,000-30,000	275 (900)	4.4 (14 5)	500 (670)	499,000 (1,100,000) 4,894	85,600 (270,000) 839	Discs 152 (168)
TM340G 1977	Isfahan water tunnel, Iran	Rock 100-2,000 (98-196) 1,400-28,000	5,600 (18,370)	3.4 (11 2)	400 (540)	370,000 (814,000) 3,630	57,300 (180,000) 561	Discs 90 (100)

[a] American ton = 2,000 lb

Komatsu Limited (Komatsu-Robbins) Rock Machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
TM490G 1978	Kouhrang development project, Iran	Rock 100-1,800 (98-176) 1,400-26,000	2,000 (6,560)	4.9 (16 1)	500 (670)	600,000 (1,320,000) 5,900	85,600 (270,000) 839	Discs 160 (176)
TM370G 1979	Kouhrang development project, Iran	Rock 100-1,800 (98-176) 1,400-26,000	6,500 (21,320)	3.7 (12 2)	400 (540)	370,000 (814,000) 3,630	57,300 (180,000) 839	Discs 95 (105)
TM370G 1979	Kouhrang development project, Iran	Rock 100-1,800 (98-176) 1,400-26,000	3,400 (11,150)	3.7 (12 2)	400 (540)	370,000 (814,000) 3,630	57,300 (180,000) 839	Discs 95 (105)

[a] American ton = 2,000 lb

Fried. Krupp GmbH. Medium to semi-hard rock machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
KTF 280 5/1967- 11/1968	Talheim Swabian Alb., S.W. Germany	Brown Jurassic	9,500 (31,000)	2.9 (9 6)	240 (321)	35,000 (77,000) 343	25,000 (181,000) 245	76.2 (75) Toothed discs with hardened inset teeth
KTF 340 1967	Mire, West Germany	Shale, limestone 1,800 (177) 26,000	At 12/1968 1,350 (4,429)	3.7 (12 1½)	240 (321)	35,000 (77,000) 343	25,000 (181,000) 245	81.3 (80) Toothed discs with hardened inset teeth

Lawrence Manufacturing Company (Subsidiary of Ingersoll-Rand Limited) Alkirk-Lawrence rock machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lbs) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
HRT-12 1964	Water tunnel, Richmond, U.S.A., New York	Shale, pegmatite with intrusions. Hard Manhattan schist 211-1,970 (21-193) 3,000-28,000	122 (400)	3.66 (12 0)	537 (720)	680,000 (1,500,000) 6,669	48,400 (350,000) 475	Button rollers 71.1 (70)
HRT-13 1968/9	Sewage tunnel, Chicago	Dolomitic limestone 1,122-2,600 (110-255) 1,600-37,000	1,970 (6,463)	4.17 (13 8)	448 (600)	680,000 (1,500,00) 6,669	65,700 (475,000) 644	Button discs Tri-cone button
007 1969	Sewage tunnel, Chicago	Dolomitic limestone 1,122-2,600 (110-255) 1,600-37,000	4,950 (16,240)	4.1 (13 5)	448 (600)	680,000 (1,500,000) 6,669	65,700 (475,000) 644	Button discs Tri-cone button

[a] American ton = 2,000 lb

Lawrence Manufacturing Company. Alkirk-Lawrence rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
006 1969	Freshwater supply, Port Huron tunnel, Mich.	Antrim shale and limestone boulders 245-1,060 (24-104) 3,500-15,000	9,620 (33,000)	5.6 (18 4)	560 (750)	680,000 (1,500,000) 6,669	79,500 (575,000) 780	Carbide button discs
006R 1972	Sewage tunnel, Rochester, New York	Sandstone and shale 214-2,182 (21-214) 3,000-31,000	8,994 (29,508)	5.61 (18 5)	671 (900)	907,000 (2,000,000) 8,900	145,000 (1,050,000) 1,420	Carbide button disc rollers
008 1969	Dorchester tunnel, Boston, Mass.	Argillite and andesite 1,693-3,569 (166-350) 24,000-50,000	10,000 (33,000)	3.8 (12 6)	448 (600)	680,000 (1,500,000) 6,669	48,400 350,000 475	Carbide button rollers
009 1969	Long haulage tunnel, Magma copper mine, Ariz.	Dacite, quartzite, limestone and conglomerate 846-3,447 (83-338) 1,200-49,000	2,592 (9,400)	3.8 (12 6)	448 (600)	680,000 (1,500,000) 6,669	65,700 (475,000) 644	Carbide button single row
010 1970	Cookhouse tunnel, Dept. of Water Affairs,, South Africa	Sandstone, siltstone, mudstone and dolorite 1,693-3,304 (166-324) 24,000-47,000	10,976 (43,000)	5 (16 6)	597 (800)	680,000 (1,500,000) 6,669	79,500 (575,000) 780	Carbide button single row
Nov 1972	Albula tunnel	Schist, limestone, and shale 280-844 (27-83) 4,000-12,000	6,100 (20,000)	3.81 (12 6)	392 (525)	680,000 (1,500,000) 6,669	48,400 (380,000) 475	Single row carbide button
Dec 1972	Paris sewer tunnel	Marl, limestone 1,050 (103) 2,110 (207) 15,000-30,000	2,680 (8,800)	4.85 (15 11)	448 (600)	680,000 (1,500,000) 6,669	65,700 (475,000) 644	Single row carbide button

[a] American ton = 2,000 lb

Mitsubishi Heavy Industries Limited (Mitsubishi-Hughes) rock machines[b]

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
126" 1968	Japanese National Railway and others, Japan	Sandstone, tuff, andesite and granite 844-1,690 (83-166) 12,000-24,000	1,000 (3,280)	3.2 (10 6)	298 (400)	349,000 (770,000) 3,423		(Ser. 12) Milled tooth rollers and carbide rollers
177" 1969-73	Japanese National Railway, Japan	Andesite, granite 844-2,110 (83-207) 12,000-30,000	2,000 (6,560)	4.5 (14 9)	560 (750)	454,000 (1,000,000) 4,452		(Ser. 12 and 15) 34 Milled tooth rollers, carbide rollers and disc cutters

[a] American ton = 2,000 lb

[b] Licensee of Hughes Tool Company

National Coal Board, United Kingdom. Rock machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
Bretby 1961-62	Trial site — limestone quarry, Breedon-on-the-Hill, Leicestershire, U.K.	Dolomitized limestone 633-2,530 av. strength 1,410 (62-248) av. strength (138) 9,000-36,000 av. strength 20,000	62.3 (205)	5.49 (18 0)	560 (750)	447,000 (986,000) 4,384		88 roller cutters 305 (300)
1965	Iron ore mine, Dragonby, U.K., United Steel Co. Ltd.	Limestone, iron ore 281-914 (28-90) 4,000-13,000	Approx. 3,230 (10,600)	5.49 (18 0)	560 (750)	447,000 (986,000) 4,384		20 disc cutters 11 roller cutters 305 (300)
1968	Experimental	Limestone 1,550 (152) 22,000		1.83 (6 0)	70.9 (95)			Discs

The Robbins Company. Rock machines

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
910-101 1953	Oahe Dam, Pierre, S. Dak.	Shale, faulted and jointed, bentonite 14-28 (1-3) 200-400	6,858 (22,500) six tunnels total by machines 910 and 930	8 (26 3)	298 (400)	45,400 (100,000) 445	38,900 (281,000) 381	Fixed and disc 113 (125)
930-102 1954 1955	Oahe Dam, Pierre, S. Dak.	Shale, faulted and jointed, bentonite 14-28 (1-3) 200-400	6,858 (22,500) six tunnels total by machines 910 and 930	8 (26 3)	298 (400)	45,400 (100,000) 445	38,900 (281,000) 381	Fixed and disc 113 (125)
101-103 1956	Sewer tunnel, Pittsburgh, Pa.	Tough shale 352-844 (35-83) 5,000-12,000		2.44 (8 0)	231 (310)	53,100 (117,000) 521	19,100 (138,000) 187	Fixed and disc 15.4 (17)
102-104 1956	Sewer tunnel, Pittsburg, Pa.	Shale and limestone interbedded 352-1,050 (35-103) 5,000-15,000		2.59 (8 6)	231 (310)	53,100 (117,000) 521	14,800 (107,000) 145	Fixed and disc 15.4 (17)
103-105 1956	Sewer tunnel, Chicago, Ill.	Hard Chicago limestone 1,266-1,760 (124-173) 18,000-25,000		2.74 (9 0)	231 (310)	53,100 (117,000) 521	19,100 (138,000) 187	Fixed 15.4 (17)
1957	Steep Rock iron mines, Atikokan, Ontario	Limonite 35-352 (3-35) 500-5,000	304.3 (1,000)	2.74 (9 0)	231 (310)	53,100 (117,000) 521	19,100 (138,000) 187	Fixed 15.4 (17)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
1957	Thetford mines, Asbestos, Quebec	Greenstone 352-1,050 (35-103) 5,000-15,000	30 (100)		231 (310)	53,100 (117,000) 521		Fixed 15.4 (17)
103-105 1960	Grants, N.M.	Sandstone 84-176 (8-17) 1,200-2,500		2.74 (9 0)	231 (310)	53,100 (117,000) 521	19,100 (138,000) 187	Fixed 15.4 (17)
131-106 1956	Humber river sewer, Toronto, Ontario	Sandstone, shale, crystalline limestone 562-1,900 (55-186) 8,000-27,000	4,510 (14,800)	3.28 (10 9)	254 (340)	142,000 (314,000) 1,393	24,300 (314,000) 238	Discs — 24 59 (65)
1961	Sewer tunnel, Ohio	Shale 352-703 (35-69) 5,000-10,000	4,510 (14,800)	3.28 (10 9)	254 (340)	142,000 (314,000) 1,393	24,300 (314,000) 238	Discs — 24 59 (65)
351-107 1960	Oahe dam, Pierre, S. Dak.	Shale, faulted and jointed bentonite seams 14-28 (1-3) 200-400	seven tunnels 2,380 (7,800)	9.0 (29 6)	507 (680)	118,000 (260,000) 1,157	94,600 (684,000) 928	Discs — 44 159 (175)
261 (Converted from 351) 1961	Gardiner dam div. tunnels, South Saskatchewan river, Canada	Soft shale, badly faulted and caving	5,580 (18,302)	7.82 (25 8)	671 (900)	118,000 (260,000) 1,157	484,000 (3,500,000) 4,747	Fixed 159 (175)
161-108 1961-73	Poatina tunnel hydro project, Tasmania, Australia	Massive mudstone, sandstone 703-1,200 (69-118) 1,000-17,000	6,860 (22,500)	4.93 (16 2)	448 (600)	279,000 (615,000) 2,736	105,000 (762,000) 1,030	33 discs 104 (115)
1964	Rhyndaston Expan., Hobart, Tasmania	Massive mudstone, sandstone 703-1,200 (69-118) 1,000-17,000	945 (3,100)	4.93 (16 2)	448 (600)	279,000 (615,000) 2,736	105,000 (762,000) 1,030	33 discs 104 (115)
1973	Shoalhaven C5 tunnel, Sydney		2,440 (8,000)	4.93 (16 2)	448 (600)	279,000 (615,000) 2,736	105,000 (762,000) 1,030	33 discs 104 (115)
71-109 1962	Sewer, McLean, Va.	Shale 352-1,050 (35-103) 5,000-15,000		2.18 (7 2)	74.6 (100)	178,000 (393,000) 1,746		14 discs 31.7 (35)
71A-109 1963	Homer-Wauseca Iron Mine, Iron River, Mich.	Limestone, iron ore 703-1,050 (69-103) 10,000-15,000	354 (1,163)	2.13 (7 0)	74.6 (100)	178,000 (393,000) 1,746		14 discs 31.7 (35)
71B-109 1963	Sewer, Chicago, Ill.	Limestone 352-1,050 (35-103) 5,000-15,000		2.13 (7 0)	74.6 (100)	178,000 (393,000) 1,746		14 discs 31.7 (35)
371-110 1963-64	Mangla dam, West Pakistan	Soft sandstone, clay with hard sandstone, lime 70-562 (7-55) 1,000-8,000	4,270 (14,000)	11.2 (36 8)	746 (1,000)	272,000 (600,000) 2,668	726,000 (5,250,000) 7,120	53 discs 32 fixed tools 290 (320)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
1968-72	Twin tube, 2nd Mersey tunnel, Liverpool, England			10.6 (34 11)	746 (1,000)	272,000 (600,000) 2,668	726,000 (5,250,000) 7,120	53 discs 32 fixed tools 290 (320)
72-112 1965-67	Sumitoma Metal Mining Co. Ltd., Japan	Chlorite, schist 703-1,410 (69-138) 10,000-20,000		2.13 (7 0)	112 (150)	178,000 (393,000) 1,746	11,800 (85,000) 116	Discs 31.7 (35)
81-113 1965	Sooke Lake- Goldstream water tunnel, Victoria, B.C.	Hard and soft schist 1,050-1,410 (103-138) 15,000-20,000	914 (3,000)	2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	15,200 (110,000) 149	18-20 discs 1 tri-cone 40.8 (45)
1968	Water tunnel, Starvation, Ut.	Sandstone and shale 70-562 (7-55) 1,000-8,000	1,620 (5,300)	2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	15,200 (110,000) 149	18-20 discs 1 tri-cone 40.8 (45)
1968-69	Alb Tun. Water Supply, Stuttgart, West Germany	Limestone 352-1,050 (35-103) 5,000-15,000	4,940 (16,200)	2.90 (9 6)	149 (200)	178,000 (393,000) 1,746	15,200 (110,000) 149	18-20 discs 1 tri-cone 40.8 (45)
1970	Water supply, Vienna, Austria	Limestone 352-1,050 (35-103) 5,000-15,000	905 (2,970)	2.90 (9 6)	149 (200)	178,000 (393,000) 1,746	15,200 (110,000) 149	18-20 discs 1 tri-cone 40.8 (45)
1972	Sewer tunnel, Geneva, Switzerland	Molasse 633-914 (62-90) 9,000-13,000	5,000 (16,405)	2.90 (9 6)	149 (200)	178,000 (393,000) 1,746	15,200 (110,000) 149	18-20 discs 1 tri-cone 40.8 (45)
1977	Drainage tunnel, Beckenreid		500 (1,640)	2.90 (9 6)	149 (200)	178,000 (393,000) 1,746	15,200 (110,000) 149	18-20 discs 1 tri-cone 40.8 (45)
1977	Drainage tunnel, Oeffingen	1,200 (117) 17,000		2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	15,200 (110,000) 149	18-20 discs 1 tri-cone 40.8 (45)
73-114 1964	Water tunnel, Payson, Ariz.	Sandstone 210-490 (20-48) 3,000-7,000	8.5 (28)	2.13 (7 10)	112 (150)	178,000 (392,700) 1,750	11,755 (85,000) 115	16 discs 31.7 (35)
73-114-1 1975	Water jet test, Skykomish, Washington	Granite-gneiss 1,400-3,160 (137-309) 20,000-45,000	12 (40)	2.13 (7 10)	112 (150)	178,000 (392,700) 1,750	11,755 (85,000) 115	16 discs 31 jets 31.7 (35)
73-114-2 1980	Buffalo, N.Y.	Limestone 910-2,100 (89-205) 13,000-30,000		2.13 (7 10)	112 (150)	178,000 (392,700) 1,750	11,755 (85,000) 115	
74-115 1965-66	Water tunnel pilot bore, Bessans, France	Schist 703-1,270 (69-125) 10,000-18,000	300 (984)	2.18 (7 2)	112 (150)	178,000 (393,000) 1,746	11,800 (85,000) 116	14 discs 31.7 (35)
1966	Pilot tunnel, Met. Paris	Limestone 70-1,050 (7-103) 1,000-1,500		2.18 (7 2)	112 (150)	178,000 (393,000) 1,746	11,800 (85,000) 116	14 discs 31.7 (35)
121-116 1965 Hybrid	Azotea Water tunnel, Chama, N.M.	Shale and sandstone 70-562 (7-55) 1,000-8,000	20,400 (67,000)	3.81 (12 6) 4.03 (13 3)	298 (400)	218,000 (480,000) 2,138	40,400 (292,000) 396	27-29 discs 1 tri-cone 68 (75)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
1968-69	Water hollow tunnel, Heber City, Ut.	Sandstone and conglomerate 352-1,050 (35-103) 5,000-15,000	4,820 (15,800)	3.94 (12 11)	298 (400)	218,000 (480,000) 2,138	40,400 (292,000) 396	27-29 discs 1 tri-cone 68 (75)
111-117 1965-66	Sewer tunnel, Baden, Switzerland	Soft sandstone 70-352 (7-35) 1,000-5,000	2,060 (6,768)	3.71 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1966	Sondier test tunnel, Julia, Sweden	Shale, conglomerate 492-1,410 (48-138) 7,000-20,000	154 (505)	3.71 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1966	Sewer tunnel, Lucerne, Switzerland	Sandstone conglomerate 633-984 (62-97) 9,000-14,000	563 (1,847)	3.71 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1967	Sewer tunnel, Gaislingen, West Germany	Limestone, marl 1,195-1,476 (117-145) 17,000-20,000	1,440 (4,718)	3.71 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1968-69	Conveyor tunnel, Blaubeuren, West Germany	Limestone 281-1,830 (28-179) 4,900-26,000	742 (2,434)	3.71 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1969-70[b]	Sonnenberg pilot tunnel, Lucerne, Switzerland	Sandstone 773-1,200 (76-118) 11,000-17,000	2,810 (9,229)	3.71 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
111-117 1971	Test bore, Sondier tunnel, Seelisberg, Switzerland	Marl 703 (69) 10,000	654 (2,146)	3.71 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1971	Utility tunnel, Lugano Switzerland	Limestone 1,200 (117) 17,000	1,300 (4,248)	3.71 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1971	Mine Addit, Schelklingen, West Germany	1,410 (138) 20,000	1,240 (4,068)	3.71 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1972	Pipeline tunnel, Obergestein, Switzerland	Schist 1,200-1,800 (117-177) 17,000-26,000	1,840 (6,037)	3.71 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1973	Friedental tunnel, Lucerne, Switzerland		500 (1,640)	3.7 (12 2)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1974-75	Lavtina-Stausee tunnel, Gigerwald, Switzerland		5,800 (19,030)	3.50 (11 6)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)
1977	Inclined shaft ('emergency' cable car), Sunnegga, Zermatt, Switzerland		1,800 (5,900)	3.50 (11 6)	224 (300)	209,000 (460,000) 2,050	44,000 (318,000) 432	26-28 discs 1 tri-cone 65.3 (72)

[a] American ton = 2,000 lb [b] Used in conjunction with Wirth Enlarging T.B.M.

The Robbins Company. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
81-118 1965-66	Sewer tunnel, Frieburg, Switzerland	Soft sandstone 422-775 (41-76) 6,000-11,000	2,150 (7,0[illegible])	2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	16,300 (118,000) 160	19 discs 40.8 (45)
1967-68	Zurichberg water supply, Zurich, Switzerland	Sandstone and marl 246-703 (24-69) 3,500-10,000	2,050 (6,716)	2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	16,300 (118,000) 160	19 discs 40.8 (45)
1969	Hydro tunnel, Wattenback, Austria	Lime, philyte 773-1,195 (76-117) 11,000-17,000	979 (3,212)	2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	16,300 (118,000) 160	19 discs 40.8 (45)
1969-70	Sewer tunnel, Flawil, Switzerland	Marl and conglomerate 633-703 (62-69) 9,000-10,000	663 (2,175)	2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	16,300 (118,000) 160	19 discs 40.8 (45)
1970	Sewer tunnel, Berne, Switzerland	Sandstone 422-703 (41-69) 6,000-10,000	873 (2,864)	2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	16,300 (118,000) 160	19 discs 40.8 (45)
1971-73	Hardhof water tunnel, Zurich, Switzerland	Sandstone 773 (76) 11,000	5,610 (18,393)	2.59 (8 6)	149 (200)	178,000 (393,999) 1,746	16,300 (118,000) 160	19 discs 40.8 (45)
1977 81-118	Water tunnel, Feickirch		700 (2,297)	2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	16,300 (118,000) 160	19 discs 40.8 (45)
1977	Power tunnel, Scheubsberg		1,638 (5,374)	2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	16,300 (118,000) 160	19 discs 40.8 (45)
1977	Rosenberg highway tunnel, Switzerland		500 (1,640)	2.59 (8 6)	149 (200)	178,000 (393,000) 1,746	16,300 (118,000) 160	19 discs 40.8 (45)
104-120 1966	Blanco water tunnel, Col.	Soft shale 70-352 (7-35) 1,000-5,000	12,800 (42,000)	3.02 (9 11)	224 (300)	172,000 (380,000) 1,687	28,400 (205,000) 279	20-25 discs 1 tri-cone 54.4 (60)
104-120-1 1968	Water supply reservoir, Pseux, Switzerland	Limestone 984-2,320 (97-228) 14,000-33,000	524 (1,719)	3.02 (9 11)	224 (300)	172,000 (380,000) 1,687	28,400 (205,000) 279	20-25 discs 1 tri-cone 54.4 (60)
1969	Mine vent tunnel, Muhlbach, Austria	Philyte, green rock 773-1,480 (76-145) 11,000-21,000	1,020 (3,334)	3.02 (9 11)	224 (300)	172,000 (380,000) 1,687	28,400 (205,000) 279	20-25 discs 1 tri-cone 54.4 (60)
104-120-1 1970	Electric cable tunnel, Berne, Switzerland	Sandstone 420-700 (41-69) 6,000-10,000	662 (2,172)	3.02 (9 11)	224 (300)	172,000 (380,000) 1,687	28,400 (205,000) 279	20-25 discs 1 tri-cone 54.4 (60)
1972	Stadtler sewer tunnel, Cham, Switzerland	Sandstone 800-1,100 (78-108) 11,000-16,000	3,336 (10,950)	3.02 (9 11)	224 (300)	172,000 (380,000) 1,687	28,400 (205,000) 279	20-25 discs 1 tri-cone 54.4 (60)
1977	Scheubsberg tunnel, Switzerland		822 (2,700)	3.22 (10 7)	224 (300)	172,000 (380,000) 1,687	28,400 (205,000) 279	20-25 discs 1 tri-cone 54.4 (60)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
1978	Milchbuck tunnel, Zurich, Switzerland		2,700 (8,858)	3.22 (10 7)	224 (300)	172,000 (380,000) 1,687	28,400 (205,000) 279	20-25 discs 1 tri-cone 54.4 (60)
104-121A 1966-67	Oso water tunnel, Durango, Col.	Soft shale 70-352 (7-35) 1,000-5,000	8,530 (28,000)	3.10 (10 2)	224 (300)	172,000 (380,000) 1,687	28,400 (205,000) 279	20-25 discs 1 tri-cone 54.4 (60)
1976	Ottawa, Ontario	Dolomitic shale	4,429 (1,350)	3.22 (10 7)	224 (300)	172,000 (380,000) 1,687	28,400 (205,000) 279	20-25 discs 1 tri-cone 54.4 (60)
181-122 1968-72	Copper mine, White Pine, Mich.	Hard shale 1,050-2,110 (103-207) 15,000-30,000	2,590 (8,500)	5.49 (18 0)	895 (1,200)	717,000 (1,580,000) 7,031	238,000 (1,720,000) 2,334	47 discs 1 tri-disc 227 (250)
181-122-1 1979	Buffalo, N.Y.	Dolomitic shale	5,739 (18,830)	5.66 (18 7)	895 (1,200)	717,000 (1,580,000) 7,031	238,000 (1,720,000) 2,334	47 discs 1 tri-disc 227 (250)
132-123 1968-69 Hybrid	South-eastern trunk sewer, Melbourne, Australia	Blocky sandstone, hard siltstone, fat plastic clay 352-1,410 (35-138) 5,000-20,000	1,110 (3,655)	3.86 (12 8)	298 (400)	249,000 (550,000) 2,442	43,400 (314,000) 426	25 discs 1 tri-cone 67.1 (74)
132-123A 1969-70	South-eastern trunk sewer, Melbourne, Australia	Blocky sandstone, hard siltstone, fat plastic clay 352-1,410 (35-138) 5,000-20,000	2,390 (7,840)	3.86 (12 8)	298 (400)	249,000 (550,000) 2,442	43,400 (314,000) 426	25 discs 1 tri-cone 67.1 (74)
132-123A-2 1970	South-eastern trunk sewer, Melbourne, Australia	Blocky sandstone, hard siltstone, fat plastic clay 352-1,410 (35-138) 5,000-20,000	3,420 (11,223)	4.39 (14 5)	298 (400)	161,000 (356,000) 1,579	43,400 (314,000) 426	21 discs fixed 67.1 (74)
132-123A-3 1970-71	Frankston sewer, Melbourne, Australia	Blocky sandstone, hard siltstone, fat plastic clay 352-1,410 (35-138) 5,000-20,000	7,270 (23,862)	4.01 (13 2)	298 (400)	161,000 (356,000) 1,579	43,400 (314,000) 426	21 discs fixed 67.1 (74)
132-123-4 1972	South-eastern trunk sewer, Melbourne, Australia	Blocky sandstone, hard siltstone, fat plastic clay 352-1,410 (35-138) 5,000-20,000	10,100 (33,000)	3.40 (11 2)	298 (400)	161,000 (356,000) 1,579	43,400 (314,000) 426	21 discs fixed 67.1 (74)
132-123-5 1974-75	South-eastern trunk sewer, Melbourne, Australia	1,050-1,410 (103-138) 15,000-20,000	7,620 (25,000)	3.66 (12)	298 (400)	161,000 (356,000) 1,579	43,400 (314,000) 426	21 discs fixed 67.1 (74)
112-124 1968-69	Reussport highway tunnel, Lucerne, Switzerland	Medium hard sandstone 281-1,050 (28-103) 4,000-15,000	3,050 (10,000)	3.30 (10 10)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	23 discs 63.5 (70)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
112-124 1969	By-pass tunnel des Laufenbach, Ruti, Switzerland	Sandstone, marl, conglomerate 773 (76) 11,000	573 (1,879)	3.30 (10 10)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	23 discs 63.5 (70)
1972	Buonas sewage tunnel, Rotkreuz, Switzerland	Molasse 598 (59) 8,500	1,610 (5,280)	3.30 (10 10)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	23 discs 63.5 (70)
1972	Lammschlucht tunnel, Fluel-Sorenberg, Switzerland	Conglomerate 1,600 (157) 23,000	1,540 (5,053)	3.30 (10 10)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	23 discs 63.5 (70)
1973	Littau sewage tunnel, Schachenhof/Emmenzopf, Switzerland		650 (2,132)	3.30 (10 10)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	23 discs 63.5 (70)
1974-75	Kiemen sewage tunnel, Cham, Risch, Switzerland	Limestone and shale 1,200 (118) 17,000	1,850 (6,068)	3.30 (10 10)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	23 discs 63.5 (70)
1977	Inclined tunnel, Sarelli, Switzerland		480 (1,575)	3.30 (10 10)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	23 discs 63.5 (70)
112-124 1977	Industrial supply tunnel, Monaco		952 (3,123)	3.30 (10 10)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	23 discs 63.5 (70)
1977	Water supply tunnel, Sines, Portugal		7,000 (22,966)	3.30 (10 10)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	23 discs 63.5 (70)
82-125 1968-70	Water and power, Tasmania, Australia	Sandstone and mudstone 703-1,200 (69-118) 10,000-17,000	2,590 (8,500)	2.44 (8 0)	149 (200)	257,000 (565,500) 2,520	18,600 (134,600) 182	17 discs 1 tri-cone 40.8 (45)
82-125-1 1972	Rosedale connector Toronto sewer, Toronto, Canada	Banded limestone and shale 492-1,050 (48-103) 7,000-[illegible]003	1,250 (4,100)	2.64 (8 8)	149 (200)	257,000 (565,500) 2,520	18,600 (134,600) 182	17 discs 1 tri-cone 40.8 (45)
1974 1977	Toronto sewer tunnel Robbins shop		2,440 (8,000)	2.64 (8 8)	149 (200)	257,000 (565,500) 2,520	18,600 (134,600) 182	17 discs 1 tri-cone 40.8 (45)
122-126 1968-69	Bermajales water tunnel, Granada, Spain	Shale and sandstone 70-703 (7-69) 1,000-10,000	7,925 (26,000)	3.81 (12 6)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	26 discs 68.0 (75)
1970-71	Tajo-Segura water project, Albacete, Spain	Limestone with clay pockets and water, incline gallery 25% grade 844-1,050 (83-103) 12,000-15,000	476 (1,561)	3.81 (12 6)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	26 discs 68.0 (75)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm² (MPa) lb/in²	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
1975 122-126-1	Trasvase Ter — Liobregat	Clay with granite, pure granite schist, limestone	1,685 (5,527)	3.81 (12 6)	298 (400)	213,000 (470,000) 2,089	41,500 (300,000) 407	26 discs 68.0 (75)
141-127 1969-70	Southwest interceptor sewer — 13A Chicago, Ill.	Limestone approx. 1,050-1,760 (103-173) 15,000-25,000	5,300 (17,400)	4.22 (13 10)	448 (600)	404,000 (890,000) 3,962	85,500 (618,000) 838	27 discs 1 tri-cone 99.8 (110)
141-127-1 1971-72	Layout and current water tunnel, Heber City, Ut.	Shale and sandstone 703-1,410 (69-138) 10,000-20,000	7,930 (26,000)	3.94 (12 11)	448 (600)	404,000 (890,000) 3,962	85,500 (618,000) 838	27 discs 1 tri-cone 99 8 (110)
1975	Montreal, Canada	n.a.	8,534 (28,000)	3.94 (12 11)				
352-128 1970-72	Heitersberg rail tunnel, Zurich, Switzerland	Sandstone (molasse) 562-844 (55-83) 8,000-12,000	2,596 (8,500)	10.67 (35 0)	746 (1,000)	717,000 (1,580,000) 7,031	353,000 (2,550,000) 3,461	62 discs 317 (349)
352-128-1 1980	Gubrist tunnel, Switzerland					717,000 (1,580,000) 7,031	353,000 (2,550,000) 3,461	62 discs 317 (349)
182-129 1970-73	Altomira water diversion, S.E. of Madrid, Spain	Limestone 844-1,050 (83-103) 12,000-15,000	9,140 + (30,000 +)	5.49 (18 0)	597 (800)	499,000 (1,100,000) 4,894	135,000 (977,000) 1,324	36 discs 166 (183)
182-129-1 1974-75	Bilbao railroad tunnel, Bilbao, Spain	Limestone 562-984 (55-97) 8,000-14,000	1,070 (3,510)	5.79 (19 0)	597 (800)	499,000 (1,100,000) 4,894	135,000 (977,000) 1,324	36 discs 166 (183)
182-129-1 1975-76	Tunnel De Orthuela, Alicante, Spain	Limestone and marl	4,130 (13,550)	5.79 (19 0)	597 (800)	499,000 (1,100,000) 4,894	135,000 (977,000) 1,324	36 discs 166 (183)
1977-78	Llauset Moralets project, Huesca, Spain		1,421 (4,660)	5.79 (19 0)	597 (800)	499,000 (1,100,000) 4,894	135,000 (977,000) 1,324	36 discs 166 (183)
182-129-2 1975	Crevillente tunnel, Murcia, Spain		4,300 (14,110)	5.48 (18 0)	597 (800)	499,000 (1,100,000) 4,894	135,000 (977,000) 1,324	36 discs 166 (183)
n.a.	Tunnel de Orijuila, Alicante, Spain		4,130 (13,550)	5.48 (18 0)	597 (800)	499,000 (1,100,000) 4,894	135,000 (977,000) 1,324	36 discs 166 (183)
n.a.	Tunnel de Portugalete, Vizcaya, Spain		1,065 (3,490)	5.48 (18 0)	597 (800)	499,000 (1,100,000) 4,894	135,000 (977,000) 1,324	36 discs 166 (183)
1979	Tunnel de Villarejo, Cuenca, Spain		4,500 (14,765)	5.48 (18 0)	597 (800)	499,000 (1,100,000) 4,894	135,000 (977,000) 1,324	36 discs 166 (183)
162-130 1970-75	Tajo-Segura water project, S.E. of Madrid, Spain	Limestone 844-1,050 (83-103) 12,000-15,000	32,200 (105,524)	4.6 (15 0) 5.11 (16 9)	448 (600)	404,000 (890,000) 3,962	87,700 (633,800) 860	32 discs 113 (125)
162-130-1 1975-76	Water tunnel outlet, Yacambu, Venezuela	Hard sandstone with shale bands 301-211 (30-207) 4,300-30,000	5,000 (16,400)	4.6 (15 0) 5.11 (16 9)	448 (600)	404,000 (890,000) 3,962	87,700 (633,800) 860	32 discs 113 (125)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
162-131[b] 1970-75	Tajo-Segura water project, S.E. of Madrid, Spain	Limestone 844-1,050 (83-103) 12,000-15,000	11,000 (36,080)	4.6 (15 0) 5.11 (16 9)	448 (600)	404,000 (890,000) 3,962	87,700 (633,800) 860	32 discs 113 (125)
123-133 1970-71	Thompson-Yarra water diversion, Melbourne	Quartzite 1,500-1,970 (152-193) 22,000-28,000	2,400 (8,000)	3.66 (12 0)	448 (600)	422,000 (930,000) 4,139	66,800 (483,000) 655	27 discs 116 (128)
123-133-1 1972	Gas pipeline, Holland-Italy	Schist 1,200-1,760 (118-173) 17,000-25,000	1,025 (3,362)	3.66 (12 0)	448 (600)	422,000 (930,000) 4,139	66,800 (483,000) 655	27 discs 116 (128)
123-133-1	Gries tunnel, Ulrichen, Switzerland			3.66 (12 0)	448 (600)	422,000 (930,000) 4,139	66,800 (483,000) 655	27 discs 116 (128)
1973	Ferden tunnel, Ferden Hohtenn, Switzerland	Soft gneiss 984 (97) 14,000	1,665 (5,641)	3.66 (12 0)	448 (600)	422,000 (930,000) 4,139	66,800 (483,000) 655	27 discs 116 (128)
123-133-1 1975	Pfander highway tunnel, Bregenz, Austria	Molasse 600-800 (59-78) 8,500-11,000	4,645 (15,240)	3.66 (12 0)	448 (600)	422,000 (930,000) 4,139	66,800 (483,000) 655	27 discs 116 (128)
1977	Kielder tunnel, England		8,000 (26,247)	3.66 (12 0)	448 (600)	422,000 (930,000) 4,139	66,800 (483,000) 655	27 discs 116 (128)
124-134 1972	Fernheiz tunnel, Zurich, Switzerland	Sandy shale to 1,700 (to 167) 24,000	3,700 (12,136)	3.71 (12 2) 3.91 (12 10)	373 (500)	302,000 (665,000) 2,962	58,800 (425,000) 577	26 discs 68.0 (75
1973	Escape tunnel, Aarau, Switzerland	Hard limestone	200 (656)	3.71 (12 2)	373 (500)	302,000 (665,000) 2,962	58,800 (425,000) 577	26 discs 68.0 (75)
1975	Nisellas Headrace-Tomils tunnel, Tomils, Switzerland	Lime schist with sandstone, layers quartz 300-700 (29-69) 4,300-10,000	6,200 (20,342)	3.71 (12 2)	373 (500)	302,000 (665,000) 2,962	58,800 (425,000) 577	26 discs 68.0 (75)
1975	Langenegg tunnel, Oesterreich, (Austria)	Marl	5,550 (18,209)	3.71 (12 2)	373 (500)	302,000 (665,000) 2,962	58,800 (425,000) 577	26 discs 68.0 (75)
125-135 1970-72	Nchanga water diversion and mining, Zambia	Granite 1,410-1,760 (138-173) 20,000-25,000	3,200 (10,500)	3.66 (12 0)	448 (600)	422,000 (930,000) 4,139	66,800 (483,000) 655	27 discs 113 (125)
163-136 1971-72	Ruhr coal Coal 16 ft drifts in West Germany	Shale and sandstone 703-1,410 (69-138) 10,000-20,000	6,800 (22,300)	4.88 (16 0)	448 (600)	408,000 (900,000) 4,001	88,000 (636,000) 863	36 discs 1 tri-disc 169 (186)
163-136-1 1976	Coal tunnel, Monopol, West Germany		7,000 (22,966)	5.4 (17 9)	448 (600)	408,000 (900,000) 4,001	88,000 (636,000) 863	36 discs 1 tri-disc 169 (186)
163-136-2 1976	Monopol coal pit, Kamen/ Westfalen, West Germany	Schist, sand schist, sandstone 301-1,055 4,300-15,000	8,300 (30-103) (27,231)	5.4 (17 9)	448 (600)	408,000 (900,000) 4,001	88,000 (636,000) 863	36 discs 1 tri-disc 169 (186)

[a]American ton = 2,000 lb [b]Bored in conjunction with 162-130.

The Robbins Company. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
126-137 1970-71	Mid-Toronto interceptor sewer, Toronto, Canada	Shale 492-1,050 (48-103) 7,000-15,000	5,850 (19,200)	3.66 (12 0)	298 (400)	249,000 (550,000) 2,442	44,900 (325,000) 440	26 or 24 discs 1 tri-cone 66.2 (73)
1973	Toronto sewer, Toronto, Ontario, Canada	Shale 492-1,050 (48-103) 7,000-15,000	3,660 (12,000)	3.66 (12 0)	298 (400)	249,000 (550,000) 2,442	44,900 (325,000) 440	26 or 24 discs 1 tri-cone 66.2 (73)
126-137-1 1974-75	Ottawa sewer Phase II, Ottawa, Canada	Limestone with vertical faults, shale, water 703-1,410 (69-138) 10,000-20,000	2,440 (8,000)	3.66 (12 0)	298 (400)	249,000 (550,000) 2,442	44,900 (325,000) 440	26 or 24 discs 1 tri-cone 66.2 (73)
211-138 1971-72	Brasimone-Suviana water tunnel, Italy	Sandstone and marl 984 (97) 14,000	4,544 (14,909)	6.40 (21 0)	671 (900)	717,000 (1,580,000) 7,032	136,000 (980,000) 1,334	41 discs 1 tri-disc 298 (328)
211-138-1 1973-75	Taloro tunnel, Sardinia	Granite, very sound to broken 703-2,460 (69-241) 10,000-35,000	2,200 (7,218)	6.65 (21 10)	671 (900)	717,000 (1,580,000) 7,032	136,000 (980,000) 1,334	41 discs 1 tri-disc 298 (328)
142-139 1971	Kitheron water tunnel, Athens, Greece	Limestone 1,050-1,410 (103-138) 15,000-20,000	1,200 (3,937)	4.27 (14 0)	448 (600)	404,000 (890,000) 3,962	71,900 (520,000) 705	32 discs 1 tri-disc 130 (143)
1972-75	Ghiona water tunnel, Ghiona, Greece	Limestone 1,055-1,406 (103-138) 15,000-20,000	14,500 (47,574)	4.27 (14 0)	448 (600)	404,000 (890,000) 3,962	71,900 (520,000) 705	32 discs 1 tri-disc 130 (143)
142-139-1 1977	Escape gallery, Yacambu, Venezuela	Sandstone and shale 301-2,110 (30-207) 4,300-30,000	61 (200)	4.27 (14 0)	448 (600)	404,000 (890,000) 3,962	71,900 (520,000) 705	32 discs 1 tri-disc 130 (143)
105-144 1972	Mt. Greenwood sewer tunnels (1) and (2) Chicago, Ill.	Limestone 1,050-2,110 (103-207) 15,000-30,000	(1) 1,660 (5,431) (2) 804 (2,638)	3.05 (10)	298 (400)	318,000 (700,000) 3,119	42,900 (310,000) 421	23 discs 68.0 (75)
105-144-1 1978	Miner's Ranch Tunnel, Oroville, California	Granite Amphibolite 2,100-3,150 (206-309) 15,000-45,000	1,270 (4,169)	3.5 (11 0)	373 (500)	404,000 890,000 3,960	71,900 (520,000) 705	24 discs 100 (110)
142-145 1972-75	Kirfi water tunnel, Athens, Greece	Limestone 1,050-1,410 (103-138) 15,000-20,000	13,000 (42,640)	4.27 (14)	448 (600)	404,000 (890,000) 3,962	71,900 (520,000) 705	32 discs 1 tri-disc 99.8 (110)
142-145-1 1975-77	Agios Nikolaos tunnel, Mornos Dam, Athens, Greece	Limestone	3,000 (9,843)	4.60 (15 6)	448 (600)	404,000 (890,000) 3,962	71,900 (520,000) 705	32 discs 1 tri-disc 99.8 (110)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
133-146 1973 Hybrid	Water tunnel, pipehead, Potts Hills, Sydney, Australia	Faults, crushed zones, high water volume, unweathered shales, siltstones and fine sandstone with dolerite dikes 141-562 (14-55) 2,000-8,000	7,800 (25,600)	3.93 (12 10)	373 (500)	316,000 (696,000) 3,099	74,700 (540,000) 733	29 discs 1 tri-disc 81.6 (90)
133-146-1 1974-75	Mt. Lyell mine, Tasmania, Australia	Andesite and schist 300-2,700 (29-265) 4,300-38,000	3,048 (10,000)	3.93 (12 10)	373 (500)	316,000 (696,000) 3,099	74,700 (540,000) 733	29 discs 1 tri-disc 81.6 (90)
164-147 1972	Atomic Laboratory Main Ring (CERN), Geneva, Switzerland	Meers molasse 562-773 (55-76) 8,000-11,000	6,388 (21,000)	4.8-5.06 (15 9-16 6)	448 (600)	499,000 (1,100,000) 4,894	88,100 (637,000) 864	36 discs 1 tri-disc 145 (160)
164-147-1 1975-76	Water tunnel, Yacambu Inlet, Venezuela	Shale with thin quartzite intrusions 350-2,100 (34-206) 5,000-30,000	14,000 (45,930)	4.8-5.06 (15 9-16 6)	448 (600)	499,000 (1,100,000) 4,894	88,100 (637,000) 864	36 discs 1 tri-disc 145 (160)
107-149 1972	Tanes drinking water, Oviedo, Asturias, Spain	Dolomitic limestone, sandstone 1,050-1,760 (103-173) 1,500-25,000	10,700 (35,097)	3.04 (10 0)	298 (400)	301,000 (665,230) 2,952	54,200 (391,791) 522	23 discs 1 tri-disc 67.1 (74)
144-151 1972 Tandem Sh. (hybrid)	Orichella and Timpagrande tunnels. SILA/Calabria southern Italy	Altered granite 700-1,400 (68-137) 10,000-20,000	4,000 (13,124)	4.27 (14 0)	645 (600)	654,000 (1,400,000) 6,326	77,700 (561,700) 762	28 discs 1 tri-disc 100 (110)
144-151-1 1979	Tunjenta tunnel, Chevon project, Columbia	Mica-schist with quartz 490-2,810 (48-275) 7,000-40,000	5,791 (19,000)	4.27 (14 0)	645 (600)	654,000 (1,400,000) 6,326	77,700 (561,700) 762	28 discs 1 tri-disc 100 (110)
231-152 1973	R.A.T.P. subway of Paris, France	Limestone molasse 1,550-2,040 (152-200) 22,000-29,000	4,700 (15,400)	7.01 (23 0)	671 (900)	718,000 (1,583,000) 7,041	175,000 (1,266,000) 1,716	45 discs 1 tri-disc 263 (290)
231-152-1 1976	Bajina Basta, Yugoslavia	Limestone 984-1,406 (97-138) 14,000-20,000	8,000 (26,246)	7.01 (23 0)	671 (900)	718,000 (1,583,000) 7,041	175,000 (1,266,000) 1,716	45 discs 1 tri-disc 263 (290)
135-153 1973	Schwelme tunnel, Wuppertal, West Germany	Dolomite, limestone, lime-sandstone 1,050-1,760 (103-173) 1,500-25,000	2,600 (8,530)	3.96 (13 0)	298 (400)	301,000 (665,230) 2,952	71,600 (517,450) 702	29 discs 1 tri-disc 90.7 (100)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm² (MPa) lb/in²	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
135-153-1 1977	Hydro tunnel, Soelk, Austria	Mica-schist with quartz 490-3,160 (48-309) 7,000-45,000	3,300 (10,827)	3.96 (13 0)	298 (400)	301,000 (665,230) 2,952	71,600 (517,450) 702	29 discs 1 tri-disc 90.7 (100)
108-154 1973	Simeri tunnel, Calabria, southern Italy	Altered granite gneiss schist 35-2,460 (3-241) 500-35,000	3,963 (13,000)	3.33 (10 11)	298 (400)	359,000 (792,000) 3,521	44,800 (324,000) 439	25 discs 1 tri-disc 68.0 (75)
108-154-1 1977	Sado-Morgavel tunnel, Sines, Portugal	Shale, sandstone inclusions 352-703 (35-69) 5,000-10,000	21,000 (68,901)	3.2 (10 7)	298 (400)	359,000 (792,000) 3,521	44,800 (324,000) 439	25 discs 1 tri-disc 68.0 (75)
91-155 1973	Crosstown waste-water interceptor Shoal Creek to Bull Creek, Austin, Tex.	Limestone shale 50-148 (5-15) 700-2,100	8,380 (27,500)	2.64 (8 8) 2.90 (9 6)	224 (300)	302,000 (665,000) 2,962	26,500 (191,599) 260	20 discs 1 tri-disc 63.5 (70)
91-155-1 1980	Calumet intercepting sewer, Chicago, Ill.	Limestone shale 50-148 (5-15) 700-2,100	5,790 (12,123)	2.6 (8 9)	224 (300)	302,000 (665,000) 2,962	26,500 (191,599) 260	20 discs 1 tri-disc 63.5 (70)
201-158 1973	Post Trasvase, Madrid, Spain	Limestone, marl, clay 352-1,050 (35-103) 5,000-15,000	11,200 (36,747) 5 tunnels	6.10 (20)	604 (810)	585,000 (1,289,000) 5,737	154,000 (1,114,000) 1,510	43 discs 279 (308)
201-158-1 1977	Padrum tunnel, Asturias, Spain	Limestone and impure limestone 562-2,390 (55-234) 8,000-34,000	3,000 (9,843)	6.10 (20)	604 (810)	585,000 (1,289,000) 5,737	154,000 (1,114,000) 1,510	43 discs 279 (308)
191-161 1974-75	Rockville Route, Section A6a, Washington, D.C.	Granite gneiss, chorite schist 703-1,760 (69-173) 10,000-25,000	5,768 (18,924)	5.79 (19 0)	671 (900)	839,000 (1,850,000) 8,228	145,000 (1,050,000) 1,422	45 discs 259 (285)
191-161-1 1975-76	Rockville Route, Section A6a, Washington, D.C.	Granite gneiss chorite schist 703-1,760 (69-173) 10,000-25,000	4,512 (14,806)	5.79 (19 0)	671 (900)	839,000 (1,850,000) 8,228	145,000 (1,050,000) 1,422	45 discs 259 (285)
1977	Rockville Route, Section Alla, Washington, D.C.	Granite gneiss chorite schist 703-1,760 (69-173) 10,000-25,000	6,707 (22,000)	5.79 (19 0)	671 (900)	839,000 (1,850,000) 8,228	145,000 (1,050,000) 1,422	45 discs 259 (285)
191-161-2 1980	Culver-Goodman, Rochester, N.Y.	Sandstone, limestone 1,800-3,280 (176-321) 25,600-46,600	8,628 (28,000)	5.79 (19 0)	671 (900)	839,000 (1,850,000) 8,228	145,000 (1,050,000) 1,422	45 discs 259 (285)
114-163 1974	Libanon gold-mine, Gold-fields of South Africa	Quartzite 1,270-2,110 (125-207) 18,000-30,000	Mine development	3.35 (11 0)	418 (560)	406,000 (896,000) 3,982	52,600 (380,000) 516	28 discs 63.5 (70)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
105-165 1974	Oslo sewer tunnel, Oslo, Norway	Calciferous shale with cyenite and diabase intrusions 352-2,110 (35-207) 5,000-30,000	5,000 (16,400)	3.15 (10 4)	373 (500)	318,000 (700,000) 3,119	42,900 (310,000) 421	23 discs 1 tri-disc 68.0 (75)
1977	Fosdalen mine, Norway	Greenstone and magnetite 1,550-3,030 (152-297) 22,000-43,000	670 (2,200)	3.15 (10 4)	373 (500)	318,000 (700,000) 3,119	42,900 (310,000) 421	23 discs 1 tri-disc 68.0 (75)
105-165-1 1977	Sulitjelma, Norway	Granite 1,690-2,890 (153-283) 24,000-41,000	360 (1,180)	3.15 (10 4)	373 (500)	318,000 (700,000) 3,119	42,900 (310,000) 421	23 discs 1 tri-disc 68.0 (75)
1978	Eidford Hydro-electric Scheme, Rwanda, W. Africa	280-1,050 (27-102) 3,000-15,000	2,800 (9,240)	3.15 (10 4)	373 (500)	318,000 (700,000) 3,119	42,900 (310,000) 421	23 discs 1 tri-disc 68.0 (75)
105-165-2 1979	Mukungwa Power Scheme, Rwanda, W. Africa	Sandstone, schist and quartzite	2,000 (6,562)	3.08 (10 1)	373 (500)	318,000 (700,000) 3,119	42,900 (310,000) 421	23 discs 1 tri-disc 68.0 (75)
262-166 1974	Bramefarine tunnel, French Alps, France	Limestone 141-422 (14-41) 2,000-6,000	3,810 (12,500)	8.08 (26 6)	671 (900)	721,000 (1,590,000) 7,071	212,000 (1,530,000) 2,079	56 discs 308 (340)
145-168 1975 45° incline slope	Hydro Penstock, Grimsel Oberaar, Switzerland	Alaskite, gneiss 703-1,760 (69-173) 10,000-25,000	812 (2,664)	4.3 (14)	634 (850)	862,000 (1,900,000) 8,454	97,900 (708,183) 960	15½ in discs
1978	Negro Ruico tunnel, Chivor project, Columbia	Schist and quartzite 700-2,460 (68-241) 10,000-35,000	10,000 (32,810)	4.3 (14)	634 (850)	862,000 (1,900,000) 8,454	97,900 (708,183) 960	15½ in discs
232-171 1976	Hydro tunnel, Split, Yugoslavia	Hard limestone 1,000-2,000 (98-196) 14,000-28,000	9,144 (30,000)	7.125 (24.3)	895 (1,200)	1,603,000 (3,534,000) 15,700	19,660 (1,706,000) 193	15½ in discs 330 (363)
233-172 1976 Shielded TBM (Hybrid)	Buckskin water tunnel, Ariz.	Andesite aglomerate, tuff 700-2,800 (69-274) 10,000-40,000	10,700 (35,000)	7.16 (23 5)	895 (1,200)	1,202,000 (2,650,000) 11,800	215,000 (1,550,000) 2,110	15½ in discs 320 (350)
212-173 1977	Seabrook cooling tunnel, N.H.	Dolomite and gneiss 1,400-2,800 (137-274) 20,000-40,000	3,964 (13,000)	6.43 (21 1)	358 (480)	907,030 (2,000,000) 8,897	183,940 (1,330,000) 1,800	15½ in discs 320 (350)
212-174 1977	Seabrook cooling tunnel, N.H.	Dolomite and gneiss 1,400-2,800 (137-274) 20,000-40,000	3,964 (13,000)	6.43 (21 1)	358 (480)	907,030 (2,000,000) 8,897	183,940 (1,330,000) 1,800	15½ in discs 320 (350)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
61-176 1977 Reef raiser	Blyvoor mine, Blyvoor, S. Africa	Quartzite 1,750 (171) 25,000		1.84 (6 ½)	149 (200)	201,900 (445,300) 1,981	182,000 (122,000) 1,787	14 (15)
61-177 1977 Reef raiser	East Driefontein mine, Carltonville, S. Africa	Quartzite 1,750 (171) 25,000		1.84 (6 ½)	149 (200)	201,900 (445,300) 1,981	182,000 (122,000) 1,787	14 (15)
185-178 1977	Upper Des Plaines 21, Contract 73-320-2S, Chicago, Ill.	Limestone and Racine formations, Brandon Bridge, Markgraf, and Romeo members of the Joliet formations	3,313 (10,870)	5.5 (18 0)	670 (900)	867,000 (1,911,000) 8,501	128,000 (924,000) 1,254	42 discs 213 (235)
185-178-1 1980	Subway tunnel, Buffalo, N.Y.	Limestone 1,120-2,460 (109-241) 16,000-35,000	2,134 (7,000)	5.95 (18 7)	670 (900)	867,000 (1,911,000) 8,501	128,000 (924,000) 1,254	42 discs 213 (235)
1010-179 1976 Shielded TBM	Vat tunnel, Ut.	Sandstone, limestone, shale 0-1,400 (0-140) 0-20,000	11,817 (38,760)	3.25 (10 8)	298 (400)	907,000 (2,000,000) 8,900	46,000 (334,000) 453	26 discs 68 (75)
116-181 1977-78	Aurland tunnel, Lysverken, Norway	Chlorite schist with calcite 420-1,050 (41-103) 6,000-15,000	6,200 (20,340)	3.5 (11 6)	447 (600)	506,000 (1,115,000) 5,000	59,490 (430,000) 580	100 (110)
1979	Lier water tunnel, Lier, Norway		3,600 (11,811)	3.5 (11 6)	447 (600)	506,000 (1,115,000) 5,000	59,490 (430,000) 580	100 (110)
129-182 1977	Sellrain-Silz tunnel, Salzburg, Austria	Hard schist, gneiss, amphibolite 980-1,550 (96-152) 14,000-22,000	4,500 (14,765)	3.9 (12 9½)	373 (500)	595,000 (1,312,000) 5,840	65,000 (469,000) 636	32 14 in discs 95 (105)
1979	Buers tunnel, Bludenz, Austria		1,550 (5,085)	3.9 (12 9½)	373 (500)	595,000 (1,312,000) 5,840	65,000 (469,000) 636	32 14 in discs 95 (105)
222-183 1977	Weller Creek, Contract 73-217-2S, Chicago, Ill.	Limestone and Racine formations, Brandon Bridge, Markgraf and Romeo members of the Joliet formation 1,000-2,100 (98-200) 14,000-30,000	6,706 (22,000)	6.70 (22)	1,194 (1,600)	1,060,000 (2,340,000) 10,410	259,000 (1,870,000) 2,540	52 15 in discs 272 (300)
1210-187	Soelk project, Salzburg, Austria	Mica-schist with quartz 490-3,160 (48-309) (7,000-44,000)	12,000 (38,290)	3.52 (11 7)	448 (600)	505,700 (1,115,000) 4,960	60,000 (430,000) 583	29 discs 91 (100)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
1210-187 1979	Bodendorf project, Austria	n.a.	9,000 (12,000)	3.52 (11 7)	448 (600)	505,700 (1,115,000) 4,960	60,000 (430,000) 583	29 discs 91 (100)
116-188 1978	Oslo sewer, Oslo, Norway	Conglomerate 700-1,000 (69-98) 10,000-14,000	7,200 (23,950)	3.50 (11 5⅞)	448 (600)	450,000 (1,000,000) 4,400	60,600 (438,000) 594	14 in discs 86 (96)
116-189 1978-81	Oslo sewer, Oslo, Norway	Conglomerate 700-1,000 (69-98) 10,000-14,000	7,200 (23,950)	3.50 (11 5⅞)	448 (600)	450,000 (1,000,000) 4,400	60,600 (438,000) 594	14 in discs 86 (96)
213-190 1978	Chicago underflow, Crawford-Calumet, Chicago, Ill.	Dolomitic limestone 1,050-2,800 (103-274) 1,900-40,000	13,000 (42,000)	6.5 (21 3)	1,600 (1,194)	910,000 (2,000,000) 8,900	205,000 (1,480,000) 2,010	15½ in discs 295 (325)
151-191 1979-82 Shielded hard rock (hybrid)	Baikal-Amur mainline service tunnel, Nijne Angarsk, Siberia, U.S.S.R.	Limestone, sandstone, shale 780-1,770 (76-174) 11,000-25,000	20,000 (65,600)	4.56 (14 11½)	597 (800)	1,226,000 (2,702,900) 12,000	106,000 (766,700) 1,000	34 14 in discs 210 (230)
92-192 1978	Stillwater tunnel, Ut.	Sandstone and shale 350-1,050 (34-103) 5,000-15,000	12,875 (42,240)	2.91 (9 6½)	298 (400)	454,000 (1,000,000) 4,452	30,953 (223,807) 2,194	24 12 in discs 112 (123)
146-193 1978-80	Thomson Yarra, Victoria, Australia	Sandstone and shale 1,400-3,600 (140-355) 20,000-51,000	6,070 (19,910)	4.1 (13 6)	559 (750)	567,000 (1,250,000) 5,560	108,816 (787,000) 1,067	160 (145)
242-195 Shielded hard rock (hybrid) 1978	Park river diversion, Hartford, Conn.	Sandstone and shale, basalt 490-1,340 (48-131) 6,970-19,000	2,755 (9,040)	7.36 (24 2)	895 (1,200)	857,304 (1,890,000) 8,400	209,525 (1,515,000) 2,000	50 × 15½ in discs 4 × 12 in centre discs 320 (350)
353-196 1978	Chicago underflow, Central-Damen, Chicago, Ill.	Hard dolomitic limestone and shale 1,200-1,750 (117-171) 17,000-25,000	7,925 (26,000)	10.8 (35 3)	1,790 (2,400)	1,250,000 (2,760,000) 12,000	486,000 (3,510,000) 4,800	65 × 15½ in discs 4 × 12 in discs (centre) 740 (810)
353-197 1979	Chicago underflow, 59th-Central, Chicago, Ill.	Dolomitic limestone 350-2,260 (34-222) 4,980-32,000	5,700 (18,804)	10.8 (35 3)	1,790 (2,400)	1,250,000 (2,760,000) 12,000	486,000 (3,510,000) 4,800	65 × 15½ in discs 4 × 12 in discs (centre) 740 (810)
1011-198 1978	V.E.P.C.O. drainage tunnels, Bath County, Va.	Shale, limestone, siltstone and mudstone 1,050-2,450 (103-240) 15,000-35,000	7,315 (24,000)	3.25 (10 8)	298 (400)	386,467 (852,000) 3,800	48,405 (350,000) 470	23 × 14 in discs 4 × 12 in discs (centre) 63 (70)
321-199 1979	Chicago underflow, Roosevelt-Ogden, Chicago, Ill.	Dolomitic limestone 840-2,250 (8[illegible]-221) 12,000-32,000	4,200 (13,780)	9.85 (32 4)	1,790 (2,400)	1,165,752 (2,570,000) 11,000	458,000 (3,304,00) 4,500	60 × 15½ discs 4 × 12 in discs (centre) 613 (675)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines – continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
321-200 1979	Chicago underflow, Ogden-Addison, Chicago, Ill.	Dolomitic limestone 840-2,250 (82-221) 12,000-32,000	6,893 (22,614)	9.85 (32 4)	1,790 (2,400)	1,165,752 (2,570,000) 11,000	458,000 (3,304,000) 4,500	60 × 15½ discs 4 × 12 in discs (centre)
202-201 1979	Westfalen coal-mine, Ruhr, West Germany	Shale and sandstone 350-1,400 (34-137) 5,000-20,000	12,700 (41,670)	6.1 (20 0)	537 (720)	635,000 (1,400,000) 6,200	131,000 (950,000) 1,300	39 × 14 in discs 4 × 12 in discs (centre) 200 (220)
214-202 1979	Blumenthal coal-mines, Ruhr, West Germany	Shale and sandstone 350-1,400 (34-137) 5,000-20,000	10,600 (34,780)	6.5 (21 4)	716 (960)	635,040 (1,400,000) 6,200	174,535 (1,262,000) 1,700	42 × 14 in discs 4 × 12 in discs (centre) 200 (220)
93-203 1979-80	Scajaquada sewer, Buffalo, N.Y.	Limestone 910-2,100 (89-206) 13,000-30,000	9,146 (30,000)	2.8 (9 6)	447 (600)	326,592 (720,000) 3,200	4,840 (35,000) 47	18 × 14 in discs 4 × 12 in discs (centre) 70 (77)
136-204 1979	Haeusling tunnel project, Zillgrtal, Austria	Dolomite and phylite 1,200 (118) 17,000	1,700 (5,580)	4.2 (13 9)	447 (600)	458,136 (1,010,000) 4,500	8,436 (61,000) 83	30 × 14 in discs 4 × 12 in discs (centre) 71 (80)
203-205 1980	East 63rd Street subway, New York	Granite-schist 280-2,430 (27-238) 4,000-34,000	1,524 (5,000)	6.15 and 6.7 (20 2 and 22 0)	895 (1,200)	889,056 (1,960,000) 8,700	162,641 (1,176,000) 1,600	42 × 15½ in discs 4 × 12 in discs (centre) 445 (490)
186-206 1979-80	Buffalo subway, Buffalo, N.Y.	Dolomitic shale 1,320-2,140 (129-210) 19,000-30,000	3,200 (10,500)	5.6 (18 6)	895 (1,200)	762,048 (1,680,000) 7,500	150,221 (1,086,200) 1,500	38 × 15½ in discs 4 × 12 in discs (centre) 213 (235)
186-207 1979-80	Buffalo subway, Buffalo, N.Y.	Dolomitic shale 1,320-2,140 (129-210) 19,000-30,000	3,200 (10,500)	5.6 (18 6)	895 (1,200)	762,048 (1,680,000) 7,500	150,221 (1,086,200) 1,500	38 × 15½ in discs 4 × 12 in discs (centre) 213 (235)
187-208 1980	Ruilmare, Bucharest, Romania	Granite-gneiss, quartzitic schist 860-1,970 (84-193) 12,000-28,000	12,000 (39,360)	5.5 (18 0)	895 (1,200)	884,520 (1,950,000) 8,700	156,970 (1,135,000) 1,500	38 × 15½ in discs 4 × 12 in discs (centre) 215 (237)
94-209 1980	Turrach project, Austria	Schist-gneiss 420-2,400 (41-235) 6,000-34,000	10,000 (32,810)	3.02 (9 10 ¼)	298 (400)	335,665 (740,000) 3,300	32,915 (238,000) 320	20 × 14 in discs 4 × 12 in discs (centre) 71 (80)
147-210 1980	Calumet system, Chicago underflow, Chicago, Ill.	Dolomitic limestone 840-2,250 (82-221) 12,000-32,000	10,975 (36,000)	4.32 (14 2)	671 (900)	551,579 (1,216,000) 5,400	87,267 (631,000) 850	31 × 15½ in discs 4 × 12 in discs (centre) 113 (125)
251-211 1980	Grand Maison, Geneve, France	Granite, granite gneiss 3,480 (341) 50,000	5,865 (19,242)	7.7 (25 3)	1,491 (2,000)	1,163,484 (2,565,000) 11,000	276,600 (2,000,000) 2,700	53 × 15½ in discs 4 × 12 in discs (centre) 380 (418)

[a] American ton = 2,000 lb

The Robbins Company. Rock machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
148-212 1980	Brattset hydropower project, Norway	Quartz-diorite intrusive; phylite 280-2,710 (27-266) 4,000-38,000	12,000 (39,372)	4.5 (14 9)	783 (1,050)	635,040 (1,400,000) 6,200	63,504 (689,000) 630	31 × 15½ in discs 4 × 12 in discs (centre) 140 (154)
148-213 1980	Brattset hydropower project, Norway	Quartz-diorite intrusive; phylite 280-2,710 (27-266) 4,000-38,000	12,000 (39,372)	4.5 (14 9)	783 (1,050)	635,040 (1,400,000) 6,200	63,504 (689,000) 630	31 × 15½ in discs 4 × 12 in discs (centre) 140 (154)
193-214 1981	Selby project, United Kingdom	Calcareous sandstone 13,000-1,476 (127-145) 18,000-21,000	13,600 (44,620)	5.8 (19)	671 (900)	578,144 (1,274,230) 5,700	130,693 (945,000) 1,300	43 × 14 in discs 182 (200)

The Robbins Company Liner-thrust shields, digger/ripper scraper shields and shaft reamers, etc.

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
341-111 1964 Liner-thrust shield pressurized face (hybrid)	Paris Metro subway, Paris, France	Mixed limestone, sandstone and clay 0-1,050 (103) 15,000	2,870 (9,430)	10.26 (33 8)	746 (1,000)	7,290,000 (16,080,000) 71,493	726,000 (5,250,000) 7,120	Discs and 180 fixed tools 454 (500)
221S-132 1970 Ripper-scraper shield (hybrid)	San Fernando water diversion, near Los Angeles, Calif.	Soft soil formations	8,230 (27,000)	6.71 (22 0)	634 (850)	3,180,000 (7,000,000) 31,186		Ripper teeth and scraper 259 (285)
113-140 1972 Liner-thrust TBM (hybrid)	Tajo-Segura water project, Albacete, Spain	Limestone 846-1,050 (83-103) 12,000-15,000	6,100 + (20,000) +	3.51 (11 6)	298 (400)	204,000 (450,000) 2,001	55,900 (404,000) 548	24 discs 68.0 (75)
143S-141 1971 Ripper-scraper shield (hybrid)	Sewer tunnel, Detroit, Mich.	Silty sand, highly compacted dry clay, to soft and sticky clay, occasional gravel, full and mixed face	3,048 (10,000)	4.41 (14 6)	448 (600)	1,270,000 (2,800,000) 12,455		Ripper scraper 97.1 (107)
143S-141 1973/4 Ripper-scraper shield (hybrid)	Sewer tunnel, Little Rock, Ark.	Sandy clay with small to medium cobble stones, gravel	1,219 (4,000)	4.41 (14 6)	448 (600)	1,270,000 (2,800,000) 12,455		Ripper scraper 97.1 (107)
143S-142 1971 Ripper-scraper shield (hybrid)	Sewer tunnel, Detroit, Mich.	Same as 143S-141 1971	3,780 (12,500)	4.41 (14 6)	448 (600)	1,270,000 (2,800,000) 12,455		Ripper scraper 97.1 (107)

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[a] American ton = 2,000 lb

The Robbins Company Liner-thrust shields etc. — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
143S-142 1973 Ripper-scraper shield (hybrid)	Mt. Clemens PCI 14, Mt. Clemens, Mich.	Clay, sand, gravel, hardpan	2,740 (9,000)	4.41 (14 6)	447 (600)	1,270,000 (2,800,000) 12,455		Ripper/scraper
361S-143 1973-5 Ripper-scraper shield (hybrid)	Castiglione rail tunnel between Rome and Florence, Italy	Consolidated slabby dry clay, and sand	7,400 (24,272)	Horseshoe 10.97 wide 9.45 high (36 wide 31 high)	1,027 (1,377)	5,440,000 (12,000,000) 53,350		Ripper scraper 558 (615)
106-148 Shielded TBM (hybrid)	La Coche hydro-electric tunnel, French Alps, France	Schist, brecchia, flysch, limestone, sandstone 703-1,760 (69-173) 10,000-25,000	7,700 (25,200)	3.02 (9 11⅛)	298 (400)	301,000 (665,000) 2,952	54,000 (392,000) 532	23 discs 1 tri-disc 67.1 (74)
75-150 1973 Oscillating	Sewer tunnel, West Lane Cove, Sydney, Australia	Hawkesbury sandstone 148-394 (15-39) 2,100-5,600	152 (500)	Rectangular with radius top and bottom 2.1 high 1.5 wide (7 high 5 wide)	104 (140)	45,400 (100,000) 445	9,220 (66,600) 90	4 discs 18.1 (20)
183S-156 1973 Ripper-scraper shield (hybrid)	New Carroltown Route D4a, Washington Metro, Washington, D.C.	Sand, clay	945 (3,100)	5.49 (18)	n.a.	2,270,000 (5,000,000) 22,262		Ripper scraper 200 (220)
183S-157 1973 Ripper-scraper shield (hybrid)	New Carroltown Route D4a, Washington Metro, Washington, D.C.	Sand, clay	945 (3,100)	5.49 (18)	n.a.	2,270,000 (5,000,000) 22,262		Ripper scraper 200 (220)
281S-159 1973 Ripper-scraper shield (hybrid)	Madrid Metro, Madrid, Spain	Clay with sand	3,500 (11,480)	8.59 (28 2)	n.a.	41,900,000 (92,400,000) 410,913		Ripper scraper 300 (331)
1977	Madrid Metro, Madrid, Spain		1,050 (3,444) 10/77 840 (2,755)	8.59 (28 2)	n.a.	41,900,000 (92,400,000) 410,913		Ripper scraper 300 (331)
109S-160 1973 Ripper-scraper shield (hybrid)	East Branch intercepting sewer, Port Richmond, N.Y.	Compact glacial till silt, sand boulders, water fill	5,180 (17,000)	3.05 (10)	261 (350)	771,000 (1,700,000) 7,561		Ripper scraper 43.5 (48)
109S-160 ex. sh. 1976 Hybrid	Eltingville sewer, Staten Island, New York	Sand, clay and fill. 1st tunnel 2nd tunnel	1,149 (3,771) 775 (2,543)	3.05 (10)	261 (350)	770,950 (1,700,000) 7,560		Ripper/scraper
109-160-2 1980	Red Hook tunnel, Brooklyn, New York	Glacial till	2,620 (8,600)	3.18 (10 5)	298 (400)	770,950 (1,700,000) 7,560		Ripper/scraper
165-162 1974 Shielded TBM (hybrid)	Channel service tunnel, Calais, France	Chalk (project delayed)	2,000 (6,560)	4.88 (16)	615 (825)	471,000 (1,039,000) 4,619	109,000 (787,800) 1,069	30 discs and 5 drag bits 245 (270)

[a] American ton = 2,000 lb

The Robbins Company Liner-thrust shields etc. — continued

Model type and year	Project location	Rock strength kg/cm² (MPa) lb/in²	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)[a]
127S-164 1974 Ripper-scraper shield (hybrid)	Berne sewer tunnel, Berne, Switzerland	Gravel with sand and clay	1,550 (5,080)	3.68 (12 1)	336 (450)	1,550,000 (3,420,000) 15,200		Ripper scraper 54.4 (60)
127-164-1 1977	Refalzaft, Sicily	Limestone and clay	3,200 (10,496) 10/77 2,200 (7,816)	3.68 (12 1)	336 (450)	1,550,000 (3,420,000) 15,200		Ripper scraper 54.4 (60)
128S-167 1975 Liner-thrust shield (hybrid)	Detroit Metro Contract PCI 24, Detroit, Mich.	Compacted sand, silty sand, clay and gravel	2,200 (7,200)	3.66 (12)	336 (450)	1,090,000 (2,400,000) 10,690		72.6 (80)
184S-169 1975 Liner-thrust shield (hybrid)	Branch Route — Section F2a, Washington Metro, Washington, D.C.	Sand and sandy clay, clay river cobbles and boulders, gravel, some water	1,372 (4,500)	5.5 (18)	358 (480)	2,720,000 (6,000,000) 26,675		200 (220)
184S-170 1975 Liner-thrust shield (hybrid)	Branch Route — Section F2a, Washington Metro, Washington, D.C.	Sand and sandy clay, clay river cobbles and boulders, gravel, some water	1,372 (4,500)	5.5 (18)	358 (480)	2,720,000 (6,000,000) 26,675		200 (220)
115S-175 1977 Digger shield (hybrid)	Yacambu water tunnel, Venezuela	Fault zone	1,000 (3,273)	3.6 (12 0)	254 (340)	206,840 (456,000) 2,028		80 (88) Probe/scraper
263S-180 Liner-thrust shield (hybrid)	Condotte d'Acqua, Rome, Italy	Soft plastic phylitic material	4,000 (13,124)	8.2 (27 1)	970 (1,300)	6,713,000 (14,800,000) 65,830		425 (468)
192S-185 1977 Liner-thrust shield (hybrid)	Caracas subway, Caracas, Venezuela	40% mica-schist, 60% clay and muddy sand	2,200 (7,218)	5.79 (19 0)	433 (580)	2,573,846 (5,675,000) 25,240		209 (230)
192S-186 1977 Liner-thrust shield (hybrid)	Caracas subway, Caracas, Venezuela	80% mica-schist, 20% clay 490-700 (48-69) 7,000-10,000	2,200 (7,218)	5.79 (19 0)	433 (580)	2,573,846 (5,675,000) 25,240		209 (230)
241S-184 1977 Shaft borer	U.S. Steel, Alabama	Sandstone, shale 0-1,400 (140) 20,000	340 (1,100) Shaft	7.44 (24 5)	500 (750)	680,000[b] (1,500,000) 6,670	226,000 (1,630,000) 2,210	56 13 in discs 227 (250)
1211SR-194 Shaft reamer 1978	Chicago underflow, Chicago, Ill.	Dolomitic limestone 1,050-2,110 (103-207) 15,000-30,000	Shaft 76.2 (250)	3.7 (12)	112 (150)	170,100 (375,000) 1,668	30,426 (220,000) 298	16 12 in discs 45 (50)

[a] American ton = 2,000 lb; [b] Includes dead weight

Subterranean Tools Inc. (Division of Kennametal Inc.)

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
TB-11 1978	Anglo-American Corporation of South Africa, Vaal Reefs gold-mine	Variable up to 4,220 (414) 60,000	Approx. 2 km	3.5 (11 6)	450 (600)	499,000 (1,100,000) 4,890	55,310 400,000 542.4	T.C. button disc cutters 90 (88)

Thyssen (Great Britain) Limited. Rock machine

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
FLP35 1975	Dawdon colliery, Co. Durham	302-1,012 (30-99) 4,300-14,000 Siltstone 264-1,617 (26-159) 3,800-23,000 Sandstone	Three tunnels 3,500 ea. (11,482) ea.	3.65 (12)	193.96 (260)	406,000 (895,000) 3,982	42,000 (304,000) 412	20/12 twin disc cutters 91.44 (90)

Union Industrielle Blanzy-Ouest. (now taken over by Bouygues, France)

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft)	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
3 M 1968	R.A.T.P. (Paris Underground) R.E.R. (Regional Express System) Exploration drift	102-1,020 (10-100) Lime soil 1,500-15,000	500 (1,640)	3 to 4 (10 10-13 2)		150,000 (301,000) 1,470		4 discs 4 arms
5 M 1968	Drift, Borie, Vianden. (Grand Duchy of Luxemburg)	816-1,224 (80-120) Schist 12,000-17,000	800 (2,630)	4-5.5 (13 2-18 0)		165,000 (364,000) 1,617		4 discs or 8 discs 4 arms

Alfred Wirth & Co. Kg. Medium to hard-rock machines — (now Wirth Maschinen GmbH)

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft) inclin.	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
TB 1-214 E 2/1967 to 6/1967	Water tunnel, Zemmkraftwerke, Ginzling, Austria	Granite gneiss	263 (863)	2.14 (7 0)				Carbide insert
TB 1-240 8/1968	Grand Emosson, Châtelard/ Switzerland	Granite	60 (197)	2.40 (7 10)				Insert
TB 11-300 E 10/1968 to 9/1969	Grand Emosson Pentshaft 'Corbes', Châtelard/ Switzerland	Granite	1,145 (3,766) 29.3°	3.00 (9 10)	460 (617)	455,000 (1,003,000) 4,462	60,500 (437,000) 593	Insert
TB 1-214 10/1968 to 1/1969	Grand Emosson 'Barberine', Châtelard/ Switzerland	Granite	415 (1,362)	2.14 (7 0)				Insert
TB 1-214 3/1969 to 12/1969	Grand Emosson Pentshaft 'Barbarine', Châtelard/ Switzerland	Granite	1,019 (3,343) 40.50°	2.25 (7 5)				Carbide insert
TB 1-240 H 7/1969 to 12/1969	HAGA tunnel, sewer tunnel, Stockholm, Sweden	Granite	450 (1,476)	2.40 (7 10)				Insert
TBE 350/770 H 770/1046 H 9/1970	Road tunnel, Lucerne, Switzerland	Sandstone and marl	2,700 (8,858)	7.70 (25 3) 10.46 (34 4)	760 (1,019)	680,000 (1,500,000) 6,669 604,000 (1,330,000) 5,923	75,000 (542,000) 736 96.000 (694,000) 941	Discs
TB 11-300 E TBE 300/600 5/1970-9/1972	Pentshaft, Wehr/Black Forest	Granite and gneiss	1,400 (4,593) 23.90°	3.00 (9 10) 6.30 (20 8)	460 (617)	455,000 (1,003,000) 4,462	60,500 (437,000) 593	Carbide insert
TB V-540 E-Sch 3/1972 5/1972	Test drilling horizontal. Colliery, Sophia Jacoba	Slate, schistous sandstone, sandstone		5.30 (17 5) 5.60 (18 4)				Discs
TB 11-300 H TBE 300/530 H 10/1971 to 9/1972	Main gallery in a colliery	Carbon, sandstone	1,600 (5,249)	5.30 (17 5)	460 (617)	440,000 (970,000) 4,315 455,000 (1,003,000) 4,462	26,000 (188,000) 255 60,500 (437,000) 593	Discs
TB 11-300 H 11/1970 7/1973	Water tunnel, Rocky Mountain, Col., U.S.A.	Granite	4,000 (13,123)	2.98 (9 9)	460 (617)	440,000 (970,000) 4,315	26,000 (188,000) 255	Insert and discs
TB 1-214 E 3/1971 to 7/1971	Tube tunnel, Meilen, Zürich	Shale	600 (1,973)	2.25 (7 5)				Discs
TB 1-240 H 10/1971 to 1/1972	Water tunnel, Orsières, Switzerland	Lime shale	1,600 (5,249)	2.40 (7 10)				Discs

Alfred Wirth & Co. Kg. Medium to hard-rock machines — continued

Model type and year	Project location	Rock strength kg/cm^2 (MPa) lb/in^2	Tunnel length m (ft) inclin.	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
TB 1-240 E 9/1971	Hydropower Station, Hirzbachwater-tunnel, Austria	Calcareous mica slate	4,845 (15,937)	2.40 (7 10)				Disc cutters and carbide insert cutters
TB V-580 H 1/1972 8/1973	Hydropower Station, Echaillon, France	Slate, crystalline slate	4,357 (14,332)	5.80 (19 0)	760 (1,019)	635,000 (1,402,000) 6,227	76,000 (551,000) 745	Discs carbide insert
TB 11-300 E 7/1972	Ventilation shaft, St. Gotthard, Motto di Dentro/ Switzerland	Slate gneiss	850 (2,796) 40.5°	3.00 (9 10) 6.40 (21 00)	460 (617)	455,000 (1,003,000) 4,462	60,500 (437,000) 593	Discs
TB IV510-H 1972	Hydro-electric Power Station, Mapragg, Sarganzer Land, Switzerland	Calcareous sandstone	6,400 (21,052)	5.10 (16 9)	620 (831)	500,000 (1,102,000) 4,903	55,000 (139,700) 54	Discs
TB 11-330 H 2/1972 3/1973	Gas tunnel, Rothorn-stollen, Switzerland	Calcareous sandstone	3,000 (9,868)	3.30 (10 10)	460 (617)	440,000 (970,000) 4,315	26,000 (188,000) 255	Discs
TB 11-328/360 H 8/1972 7/1973	Glacier-Metro, Kaprun, Austria	Crystalline slate	3,200 (10,499) 23.9°	3.60 (11 10)	460 (617)	440,000 (970,000) 4,315	26,000 (188,000) 255	Discs and carbide inserts
TB 11-300 H 11/1972	Tschingelmad, Switzerland		1,200 (3,937)	3.10 (10 2)	460 (617)	440,000 (970,000) 4,315	26,000 188,000) 255	Discs
TB 1-253 H 3/1973	Inclined shaft, Hohtenn-Lotschental	Gneiss	1,100 (3,609) 1,103 (3,619) 29.3°	2.53 (8 4)	380 (509)	280,000 (617,000) 2,746	17,500 (127,000) 172	Carbide insert cutters
TB 11-300 H 2/1973 10/1974	Pressure gallery, Hohtenn-Lotschental	Crystalline slate	4;300 (14,144)	3.00 (9 10)	460 (617)	440,000 (970,000) 4,315	26,000 (188,000) 255	Disc cutters Carbide insert cutters
TB 11-370 H 7/1973 12/1974	Pressure gallery, Sarelli Sarganser Land	Calcareous sandstone	4,800 (15,789)	3.70 (12 2)	460 (617)	440,000 (970,000) 4,315	26,000 (188,000) 255	Disc cutters
TB V 580 H 2/1974	Pressure water gallery, Arc Isère, Spie-Batignolles	Sandstone, slate	9,675 (31,742)	5.80 (19 0)	760 (1,019)	635,000 (1,400,000) 6,227	76,000 (551,000) 745	Disc cutters
TB11-300E 3/1974 9/1974	Ventilation shaft pilot hole, St. Gotthard, Bäzberg	Granite	476 (1,565) 37.8°	3.00 (9 10)	460 (617)	455,000 (1,003,000) 4,462	60,500 (437,000) 593	Carbide inserts
TB11-359H 6/1975	Express motor road tunnel, pilot drill, Pfänder, near Bregenz	Lime, sandstone	3,350 (11,019)	3.59 (11 10)	460 (617)	440,000 (9,700,000) 4,315	26,000 (188,000) 255	Discs
TB1-253H 8/1975	Inclined gallery, Chiosta Piastra, Italy	Crystalline slate (gneiss)	1,080 (3,552)	2.53 (8 4)	380 (509)	280,000 (617,000) 2,746	17,500 (127,000) 172	Carbide inserts

Alfred Wirth & Co. Kg. Medium to hard-rock machines – continued

Model type and year	Project location	Rock strength kg/cm² (MPa) lb/in²	Tunnel length m (ft) inclin.	Machine diameter m (ft in)	Cutter head kW (hp)	Thrust kg (lb) kN	Torque kg m (lb ft) kN m	Type cutter and machine weight t (tons)
TB11-346H **9/1974**	**Pressure gallery, Rotlech, Heiterwang**	Limestone	4,600 (15,131)	3.46 (11 5)	460 (617)	440,000 (970,000) 4,315	26,000 (188,000) 255	Discs
TB11-300E **9/1975**	**Pressure shaft, Rovina, Entracque**	**Crystalline slate (gneiss)**	1,080 (3,540) 42.0°	3.00 (9 10)	460 (617)	455,000 (1,003,000) 4,462	60,500 (437,000) 593	Carbide inserts
TB1-280H **12/1975**	**Feed gallery, Lavtina**	Limestone	6,000 (19,736)	2.80 (9 3)	380 (509)	280,000 (617,000) 2,746	17,500 (127,000) 172	Discs
TB11-325H **10/1975**	**Feed gallery, Acquedotto delle Capore, Vianini**	Limestone	7,000 (23,026)	3.25 (10 8)	460 (617)	440,000 (970,000) 4,315	26,000 (188,000) 255	Discs
TBS-11-340H **1976**	**Tunnel in gold-mine, Anglo-American, South Africa**	**Quartzite, granite**		3.40 (11 2)				Carbide inserts
TB-11 300E **6/1976**	**Pressure shaft, Chiotas-Entracque**	**Crystalline slate (gneiss)**	1,080 (3,552) 42.0°	3.00 (9 10)	460 (617)	455,000 (1,003,000) 4,462	60,500 (437,000) 593	Carbine inserts
TB-11 330H **1/1977**	**Feed gallery, Guamacan, Vianini, Venezuela**	**Sandstone**	13,000 (42,763)	3.30 (10 10)	460 (617)	440,000 (970,000) 4,315	26,000 (188,000) 255	Discs

Japanese Licensee Rock Machine Manufacturers*

Ishikawajima Harima (Habegger/Atlas Copco)	4 machines 1967-73;
Kawasaki Heavy Industries (Jarva/Atlas Copco)	2 machines 1971 and 1973;
Komatsu (Robbins)	11 machines 1964-79;
Mitsubishi Heavy Industries (Hughes Tool)	2 machines 1967 and 1968.

Other manufacturers of rock tunnelling machines not included in general list: U.S.S.R. and China.

*Richard J. Robbins, Lecture 1: History of rock boring. Economics and management of underground rock boring, The South African Institute of Mining and Metallurgy, 4-8 Feb., 1980.

Mechanized Shield Machine Manufacturers

Markham & Company Limited, U.K.
Sir Robert McAlpine & Sons Ltd, U.K.*
Robert L. Priestley Ltd., U.K.
Jarva Inc., U.S.A.
Kinnear Moodie & Company Ltd., U.K.*
Bade & Theelen GmbH, West Germany
Tunnelling Equipment (London) Ltd., U.K.
Calweld Inc. — Division of Smith International, U.S.A.*
W. Lawrence & Sons (London) Ltd., U.K.
Westfalia Lunen, West Germany
Arthur Foster, U.K.*
Lovat Tunnel Equipment Inc., Ontario
M & H Tunnel Equipment, U.S.A.*
Machinoexport U.S.S.R.
Aubrey Watson Ltd., U.K.*
Zokor International Ltd., U.S.A.
Decker Mnf. Co., U.S.A.
Memco, U.S.A.*
Robbins Company, U.S.A.
Elgood Mayo Corp., U.K.
Milwaukee Boiler Manufacturing Co., U.S.A.
Stelmo Ltd., U.K.
Marcon Ltd., U.K.
Martin Herrenknecht GmbH, West Germany
Komatsu Ltd., Japan
Nihon Koki Co., Ltd., Japan
Mitsubishi Heavy Industries Ltd., Japan
Mitsui Engineering & Shipbuilding Co., Ltd., Japan
Hitachi Construction Machinery Company, Ltd., Japan
Ishikawajima-Harima Heavy Industries Co. Ltd., Japan
Hitachi Shipbuilding & Engineering Co. Ltd., Japan
Kawasaki Heavy Industries Co. Ltd., Japan
Iseki Poly-Tech., Japan
R. Schäfer & Urbach GmbH, West Germany

*These companies have either stopped manufacturing soft-ground machines or have ceased trading.

Slurry and Earth Pressure Balanced Machine Manufacturers

Markham & Co. Ltd., U.K.
Robert L. Priestley Ltd., U.K.
Orenstein & Koppel, AG, West Germany
Gardner Engineering Corp., U.S.A.*
Wayss & Freytag, AK, West Germany
Komatsu Ltd., Japan
Mitsubishi Heavy Industries Ltd., Japan
Mitsui Engineering & Shipbuilding Co. Ltd., Japan
Hitachi Construction Machinery Co. Ltd.
Ishikawajima-Harima Heavy Industries Co., Ltd., Japan
Hitachi Shipbuilding & Engineering Co. Ltd., Japan
Kawasaki Heavy Industries Co. Ltd., Japan
Iseki Poly Tech., Japan

* These companies have either stopped manufacturing soft-ground machines or have ceased trading.

Boomheader Machines

AEC Inc. (formerly Alpine Equipment Corp.)

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
Super ROC-MINER, Model 330	1977	Field-interchangeable milling or ripping head	Gathering arms	27	123-205 (165-275)	290-373 (390-500)	41.65 (41)
AEC Gantry Miner (Jumbo)	1978	Milling or ripping head	Gathering arms or L.H.D. vehicle	2	Max. 2 × 205 (Max. 2 × 275)	597 (800)	70 (68.9)
ROC-MINER E-Series and H-Series	1979	Ripping head	Gathering arms	31	75-112 (100-150)	150-187 (200-250)	24 (23.63)

Anderson Boyes

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
Bretby roadheader Mark IIA (Dosco tracks)	1964	Milling	Gathering arm	2	37 (50)	74 (100)	26.4 (26)

Anderson Strathclyde Limited

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
RH I	1969	Milling	Gathering arm		50 (65)	100 (130)	27.4 (27)
RH 10	1970-71	Milling	Gathering arms		50 (65)	100 (130)	25.4 (25)
RH 20 (crawler or walking base)	1975	Milling	Twin-flight loading chains		50 (65)	100 (130)	24.3 (24)
Boom miner (crawler or walking base)	1975-76	Milling	Encircling conveyor		60 (80)	120 (160)	22 (21.5)
RH 22 (crawler or walking base)	1975-76	Milling	Gathering arm		90 (120)	140 (185)	35 (34.4)
RH1/3 (crawler or walking base)	1975-76	Milling	Gathering arm		90 (120)	180 (240)	50 (49.2)

Distington Engineering Company Limited

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
Bretby roadheader (Dosco tracks)	1964	Milling	Gathering arm	2	37 (50)	74 (100)	26.4 (26)

Dosco Overseas Engineering Limited

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
Roadway cutter	1953-69	Milling	Encircling conveyor		37 (50)	85 (115)	18.28 (18)
Mark 2A	1970	Milling	Encircling conveyor		49 (65)	104 (140)	23.36 (23)
Twin-boom miner TB 600	1971	Two milling heads	Gathering arms (flight conveyor folding on return)		90 (120)	650 (900)	73.15 (72)
Mark 3		Milling	Gathering arms		143 (190)	300 (400)	60.96 (60)
SL 120	1971	Milling	Gathering arms		75 (100)	164 (220)	23.36 (23)
U.T.R. crawler mounted	1973	Milling	Bulldozer blade		37 (50)	86 (115)	18.28 (18)
LH 100	1976	Milling	Encircling single-strand conveyor		49 (65)	105 (140)	30.48 (30)

Gebr. Eickhoff Maschinenfabrik (Gebr. Eickhoff)

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
EV2		Ripping	Gathering arms		80 (107)	173 (232)	33.52 (33)
EVA 160		Ripping	Gathering arms		160 (215)	310 (416)	52.83 (52)
EVR 160		Milling	Gathering arms		160 (215)	340 (456)	81.28 (80)
EVR 200		Milling	Gathering arms				
EV 100A					160 (215)	340 (456)	81.28 (80)
EV 100B		Milling	Gathering arms		160 (215)	340 (456)	81.28 (80)
EVR 120		Milling	Gathering arms		160 (215)	340 (456)	81.28 (80)

Machinoexport (U.S.S.R.)

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
PK3 and PK-3M (Evolved from Hungarian F-4)	1953	Milling	Encircling conveyor		32 (43)	78 (104)	10.8 (10.8)
PK-9		Milling	Gathering arms		90 (118)	173 (232)	36 (35.4)

Mannesman Demag AG (formerly Demag AK)

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
'Unicorn' VS1 (Hybrid)	1962	Milling — spiral pick arrangement	Encircling flight conveyor	2	25.3 (34)	47.7 (64)	12.5 (12.7)
Articulated Boomheader Excavator	1971	Milling		8	119.3 (160)	160.3 (215)	60 (60.96)
VS2E (Hybrid)	1968-72	Milling — spiral pick arrangement	Encircling flight conveyor	7	55.95 (75)	86.53 (116)	42.67 (42)
VS3	1978	Milling	Twin flight conveyor	5	160 (215)	264 (354)	71.12 (70)

Mavor & Coulson Ltd.

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
Bretby roadheader Mark IIB (Lee-Norse tracks)	1964	Milling	Gathering arm	2	37 (50)	74 (100)	26.4 (26)

National Coal Board

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
Bretby roadheader Mark I	1962	Milling	Gathering arms	1	30 (40)	60 (80)	20 (20)
Bretby roadheader Mark II	1963	Milling	Gathering arms	8	30 (40)	78 (105)	20 (20)
MRDE Boom ripper	1969	Milling	None	2	30 (40)	87.5 (130)	20 (20)

Paurat GmbH (under Dosco licence)

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
SVM	1967	Milling	Encircling conveyor	15	50 (67)	88 (118)	20 (20)

Paurat GmbH

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
E124	1973	Milling	Flight conveyor	1	55 (74)	85 (141)	21 (21)
E141	1974	Milling	Gathering arms	10	55 (74)	85 (141)	24.4 (24)
Twin-boom miner	1970	Twin booms milling	None (separate loader)	1	110 (150)	242 (324)	50.8 (50)
E134 U.K. (Titan) West Germany (Roboter)	1975	Milling spiral pick arrangement	Two single-chain conveyors around deflector sheaves	31	200 (268)	300 (402)	62.9 (62)
E169	1978	Milling	Gathering	9	100 (134)	187 (206)	39.6 (39)

Paurat GmbH

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
Trench-cutting machine (crawler mounted)	1975	Articulated boom — milling — spiral pick arrangement	Separate excavator	9	200 (268)	400 (536)	101.6 (100)

Paurat Special-Purpose Machines

GKL	1969	Cutting unit in walking frame with two booms.
PTF70	1970	With two booms.
PTF70A	1971	With telescoping boom for maximum cross-section of 144.5 m^2 to be cut from one position.
E124	1973	For small cross-sections, special loader for sticky material.
E128	1973	For large cross-sections without loader.
E130	1973	Similar to the E128, with loader.
E133	1973	Light machine mounted on an excavator chassis.
E135	1974	For circular cross-sections.
E136	1974	For railway tunnels in abrasive rock.
E149	1974	With impact ripper.
E141	1975	With gathering arm loaders.

Voest-Alpine (formerly Alpine Montan) (licence granted by Nikex in conjunction with Orszago Bányagépgyártó Vállalat)

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
F-6A	1964	Ripping (twin head)	Gathering arms (single-chain conveyor)		30 (40)	60 (80)	12.19 (12)

Alpine Montan/Schäffer & Urbach

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
Circular cutting equipment	1977	Ripping (twin head — with different diameters)	Chain conveyor		Cutterheads on twin booms driven by one motor		

Voest-Alpine

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
Alpine miner AM50	1971	Ripping (twin head)	Gathering arms		100 (136)	155 (211)	24.38 (24)
Alpine miner AM100	1976	Ripping (twin head)	Gathering arms		228 (306)	456 (612)	75.18 (74)

Voros Csillag (Red Star) Tractor Works

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
	1949	Ripper chain-driven cutter head with contra-rotating discs fitted with picks					
F-Type 1	1949	Ripper chain-driven cutter head with contra-rotating discs fitted with picks					
F-Type 2	1949	Ripper cutter-head with hemi-spherical discs fitted with picks			Motor at base of cutting boom	Separate motor for traction	
F-3, F-4, F-5, Serial 'Zero', 'Serial-1'	1949	Ripper cutter-head with hemi-spherical discs fitted with picks			Motor at base of cutting boom	Separate motor for traction	
F-Type	1950-51	Ripper cutter-head with hemi-spherical discs fitted with picks			Motor at base of cutting boom	Separate motor for traction	
F-6	1956-64	Ripping (first unit with twin heads)	Gathering arms		30 (40)	60 (81)	10.7 (10.5)

Westfalia Lünen

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power kW (hp)	Total installed machine power kW (hp)	Machine weight t (tons)
Büffel WAV 170 211 100-211 119	1972-79	Radial cutting head	Platform with loading arm	20	200 (268)	290 (390)	53.8 (53)
WAV 178 211 120-211 122	1975-79	Radial cutting head	Platform with loading arm	3	200 (268)	290 (390)	73.15 (72)
Bison WAV 200 211 200-211 203	1975-78	Radial cutting head	Platform with loading arm	4	200 (268)	310 (416)	74.16 (73)
Frettchen FL-34	1976	Radial cutting head	Conveyor boom	1	13 (17.5)	22 (30)	3.04 (3)
FL-1-20 40 001-40 008	1978	Radial cutting head	Conveyor boom	8	20 (27)	25 (34)	3.55 (3.5)
Wühlmaus FL-13 13 001-13 027	1967-73	Radial cutting head	Conveyor boom	27	14 (19)	37 (50)	5.08 (5)
FL-31 31 001-31 014	1973-77	Radial cutting head	Conveyor boom	14	14 (19)	52 (71)	6.60 (6.5)
FL-2-25 39 001-39 003	1978-79	Radial cutting head	Conveyor boom	3	25 (34)	45 (61)	5.89 (5.8)
Fuchs (Prototype FL-SO1)	1963	Radial cutting head	Conveyor boom	1	15 (21)	23.8 (32)	5.08 (5)
FL-SO1 1001-1014	1965-67	Radial cutting head	Conveyor boom	11	15 (21)	23.8 (32)	5.08 (5)
FL-RO2 2001-2012	1965-66	Radial cutting head	Conveyor boom	10	15 (21)	23.8 (32)	5.08 (5)
FL-RO4 4001	1968	Radial cutting head	Conveyor boom	1	33 (45)	53 (72)	6.40 (6.3)
FL-3R-33 4002-4021	1972-78	Radial cutting head	Conveyor boom	20	33 (45)	53 (72)	6.40 (6.3)
FL-SO5 5001	1967	Radial cutting head	Conveyor boom	1	24 (33)	37.5 (51)	6.09 (6)
FL-35-33 5002	1967-79	Radial cutting head	Conveyor boom	42	24 (33)	37.5 (51)	6.09 (6)
FL-RO6 6002-6047	1966-78	Radial cutting head	Conveyor boom	44	24 (33)	37.5 (51)	5.58 (5.5)
FL-14 14 001	1978	Radial cutting head	Conveyor boom	1	33 (45)	55 (75)	6.09 (6)
FL-20 20 001	1978	Radial cutting head	Conveyor boom	1	22 (30)	33 (45)	9.14 (9)
FL-21 21 001-21 006	1969-70	Radial cutting head	Conveyor boom	6	24 (33)	37 (50)	3.55 (3.5)
FL-22 22 001	1969	Radial cutting head	Conveyor boom	1	35 (47)	86 (117)	6.60 (6.5)
FL-S25 25 001-25 002	1969-76	Radial cutting head	Conveyor boom	2	14 (19)	29.5 (40)	4.57 (4.5)
FL-35 35 001-35 002	1976	Radial cutting head	Conveyor boom	2	33 (45)	45 (61)	6.60 (6.5)
FL-3R-40 37 001-37 007	1977-79	Radial cutting head	Conveyor boom	7	40 (54)	73 (99)	9.14 (9)
Dachs FL-R12 12 001-12 021	1967-75	Radial cutting head	Conveyor boom	21	30 (41)	70 (96)	13.20 (13)
FL-R23 23 001	1969	Radial cutting head	Conveyor boom	1	53 (72)	101 (137)	13.20 (13)
FL-4R-53 23 002-23 046	1969-79	Radial cutting head	Conveyor boom	45	53 (72)	101 (137)	13.20 (13)

Westfalia Lünen

Model no.	Year of manufacture	Cutter-head type	Loading system	Number of this model manufactured	Cutter-head power k W (hp)	Total installed machine power k W (hp)	Machine weight t (tons)
FL-24 24 001-24 004	1972-76	Radial cutting head	Conveyor boom	4	35 (47)	86 (117)	12.19 (12)
FL-S26 26 001	1970	Radial cutting head	Conveyor boom	1	30 (47)	70 (96)	14.22 (14)
FL-R29 29 001	1971	Radial cutting head	Conveyor boom	1	53 (72)	101 (137)	13.20 (13)
FL-38 38 001-38 002	1976	Radial cutting head	Conveyor boom	2	35 (47)	75 (102)	6.09 (6)
Luchs FL-5R-90	1975-78	Radial cutting head	Conveyor boom		110 (150)	182 (248)	25.4 (25)
32 001-32 004	1975-78			4			
42 005-42 006	1979			2			
46 007-46 010				4			
FL-6R-110 43 001-43 002	1978-79	Radial cutting head	Conveyor boom	2	110 (150)	202 (275)	38.60 (38)
Firstenfreise FF-5R-90 36 001-36 004	1976-79	Radial cutting head	Conveyor boom	4	90 (122)	137 (186)	23.36 (23)

Mounted Impact Breakers – continued

Manufacturer	Model no.	Blow energy kg m (ft lb)	Blows per minute	Type of accumulator or spring	Total energy per unit time kg m/min (ft lb/min)	Hydraulic or pneumatic	Weight kg (lb)	Tool shank size (dia) mm (in)
Allied Steel & Tractor Products, U.S.A.	Rapid Ram Model 33	27.66 (200)	1,250		35,000 (250,000)	H	317 (700)	63.5 (2½)
Allied Steel & Tractor Products, U.S.A.	Ho-Ram* Super 79	415 (3,000)	250	none	103,000 (750,000)	P	1,632 (3,600)	146 (4¾)
Allied Steel & Tractor Products, U.S.A.	Ho-Ram 7000B	138 (1,000)	400	none	55,000 (400,000)	P	499 (1,100)	101.6 (4)
Allied Steel & Tractor Products, U.S.A.	Ho-Ram Model 250	138 (1,000)	450	none	62,100 (450,000)	P	431 (950)	89 (3½)
Manufactured by Allied for Krupp in U.S.A.	Hy-Ram* Model 65	104 (750)	550		57,000 (412,500)	H	453 (1,000)	82.5 (3¼)
Manufactured by Allied for Krupp in U.S.A.	Hy-Ram Model 77	104 (750)	550		57,000 (412,500)	H	408 (900)	82.5 (3¼)
Manufactured by Allied for Krupp in U.S.A.	Hy-Ram Model 88	180 (1,300)	450		80,905 (585,000)	H	726 (1,600)	101.6 (4)
Manufactured by Allied for Krupp in U.S.A.	Hy-Ram Model 99	277 & 138 (2,000 & 1,000) at 450 & 900 blows per minute respectively	450-900		124,400 (900,000)	H	451 (3,200)	133.3 (5¼)
Anderson/Mavor, U.K.**	MC3A/4R	150 (1,085)	600		90,000 (651,000)	H	n.a.	
Champion**	H-16	2,212 (16,000)	110		243,000 (1,760,000)	H	n.a.	
Compair, U.K.**	Holbuster	248 (1,800)	180		45,000 (324,000)	H	635 (1,402)	
Contech**	HD-7	331 (2,400)	200		66,000 (480,000)	H	544 (1,200)	

Mounted Impact Breakers – continued

Manufacturer	Model no.	Blow energy kg m (ft lb)	Blows per minute	Type of accumulator or spring	Total energy per unit time kg m/min (ft lb/min)	Hydraulic or pneumatic	Weight kg (lb)	Tool shank size (dia) mm (in)
Contech**	HD-10	318 (2,300)	350		11,000 (805,000)	H	789 (1,740)	
Contech**	HD-5	138 (998)	450		62,000 (450,000)	H	489 (1,080)	
Contech**	HD-3	69 (500)	650		45,000 (325,000)	H	329 (727)	
Contech**	Miniram 125	48 (350)	750	none	36,000 (262,000)	P	235 (520)	
C.T.I. West Germany**	Nutcracker HD7	297 (2,150)	200		59,000 (430,000)	H	499 (1,100)	
Demag, West Germany**	VR40	1,300 (9,403)	138	none	179,000 (1,300,000)	P	5,499 (12,125)	
Demag, West Germany**	VR15	366 (2,647)	215	none	79,000 (569,000)	P	2,300 (5,071)	
Demag, West Germany**	DKB-750	276 (1,996)	600	none	166,000 (1,200,000)	P	870 (1,918)	
Demag, West Germany**	DKB-375	138 (998)	600	none	83,000 (600,000)	P	446 (984)	
Eimco**	Impactor	207 (1,500)	400		83,000 (600,000)	H	n.a.	
Furukawa**	1200	240 (1,736)	460	none	110,000 (800,000)	P	1,139 (2,513)	
Furukawa**	750	170 (1,230)	450	none	76,000 (550,000)	P	749 (1,653)	
Gardner Denver, U.S.A.	CB99A		101	none	n.a.	P	150 (330)	76 (3)
Guest**	125	96 (700)	500	none	48,000 (350,000)	P	204 (450)	
Gullick Dobson Ltd, U.K.	G.D. 3000	295 (2,220)	Variable 0-600	Internal nitrogen	177,000 (1,330,000)	H	820 (1,804)	102 (4)
Gullick Dobson Ltd, U.K.	G.D. 2000	204 (1,475)	Variable 0-600	Internal nitrogen	122,000 (885,000)	H	465 (1,025)	89 (3.5)
Hausherr**	HNM-1	210 (1,519)	400		84,000 (610,000)	H	n.a.	
Hausherr**	HNL-1	90 (651)	550		49,000 (360,000)	H	n.a.	
HED**	HB-500	69 (500)	500		35,000 (250,000)	H	244 (538)	
Hughes Tool Co., U.S.A.	Impactor AA-750Wg	17.3 (125)	1,000	Internal mechanical spring	17,300 (125,000)	H	105 (233)	47.63 (1-7/8)
Ingersoll-Rand, U.S.A.	Goblin G500	69 (500)	600	Sliding piston accumulator	41,000 (300,000)	H	527 (720)	76.2 (3)
Ingersoll-Rand, U.S.A.	Goblin G900	124 (900)	420	Sliding piston accumulator	52,000 (378,000)	H	363 (800)	76.2 (3)
Ingersoll-Rand, U.S.A.	Goblin G1100B	165 (1,100)	588	Sliding piston accumulator	97,000 (646,000)	H	500 (1,100)	76.2 (3)
Ingersoll-Rand, U.S.A.	Air Goblin ABM500	96.6 (698)	600	none	57,000 (420,000)	P	291 (640)	76.2 (3)
Ingersoll-Rand, U.S.A.	Air Goblin ABM1000	165.6 (1,200)	600	none	99,000 (720,000)	P	454 (1,000)	101 (4)

Mounted Impact Breakers – continued

Manufacturer	Model no.	Blow energy kg m (ft lb)	Blows per minute	Type of accumulator or spring	Total energy per unit time kg m/min (ft lb/min)	Hydraulic or pneumatic	Weight kg (lb)	Tool shank size (dia) mm (in)
I.P.H.**	202B	95 (687)	400		38,000 (270,000)	H	249 (551)	
Joy Manufacturing Co., U.S.A.	411 HEFTI	829 (6,000)	65	Nitrogen	54,000 (390,000)	H	1,179 (2,600)	
Joy Manufacturing Co., U.S.A.	514 HEFTI	2,765 (20,000)	25	Nitrogen	69,000 (500,000)	H	1,089 (2,400)	127 (5)
Joy Manufacturing Co., U.S.A.	206 HEFTI	138 (1,000)	200	Nitrogen	27,600 (200,000)	H	159 (350)	51 (2)
Kent Air Tool Co., U.S.A.	999	138 (1,000)	600	none	83,000 (600,000)	P	376 (829)	89 (3½)
Kent Air Tool Co., U.S.A.[a]	KB-999-H	138 (1,000)	600	none	83,000 (600,000)	P	567 (1,250)	89 (3½)
Kent Air Tool Co., U.S.A.[b]	KB-999-S	138 (1,000)	600	none	83,000 (600,000)	P	590 (1,300)	89 (3½)
Kent Air Tool Co., U.S.A.	555	69 (500)	600	none	44,490 (300,000)	P	220 (485)	64 (2½)
Kent Air Tool Co., U.S.A.	2000	276 (2,000)	600	none	165,960 (1,200,000)	P	744 (1,640)	133 (5¼)
Krupp & Co., West Germany[c]	HM 401	55 (400)	550		30,000 (220,000)	H		
Krupp & Co., West Germany	HM 110	46 (332)	700-1,000		45,900 (331,000)	H	170 (374)	65 (2.55)
Krupp & Co., West Germany	HM 200	82 (590)	480-650		53,000 (383,000)	H	530 (1,168)	80 (3.14)
Krupp & Co., West Germany	HM 600	194 (1,400)	360-500		96,700 (699,000)	H	925 (2,039)	100 (3.93)
Krupp & Co., West Germany[d]	HM 800	316 (2,280)	300-450 (600-900)		142,000 (1,020,000)	H	1,480 (3,263)	135 (5.31)
Krupp & Co., West Germany[d]	HM 900	377 (2,730)	300-450 (600-900)		169,500 (1,220,000)	H	1,480 (3,263)	135 (5.31)
Krupp & Co., West Germany[d]	HM 1200	459 (3,320)	250-400		183,000 (1,320,000)	H	1,650 (3,637)	150 (5.90)
Lee Norse**	Hard Nose-1	165 (1,200)	600		99,000 (720,000)	H		
Lemand**	Shand-Macol	272 (1,970)	200		545,000 (394,000)	H	522 (1,151)	
Lemand**	Overarm	240 (1,736)	180		43,200 (312,000)	H		
Lemand**	Shand Hammer	239 (1,730)	180		43,000 (311,000)	H	521 (1,150)	
McDowell**	Powa Ram	1,383 (10,000)	85		117,000 (850,000)	H	1,530 (3,375)	
Mindev**	BR 120	159 (1,155)	1,250		199,000 (1,440,000)	H	306 (675)	
Mindev**	380	134 (976)	500		67,000 (488,000)	H		
Mindev**	BR-40	117 (850)	2,000		235,000 (1,700,000)	H	204 (450)	
Mindev**	Woodpecker	8 (65)	1,500		13,000 (97,000)	H	39 (88)	
MKT**	RB-8	575 (4,158)	225	none	129,000 (935,000)	P	2,751 (6,065)	
MKT**	RB-4	345 (2,500)	275	none	95,000 (687,000)	P	1,757 (3,975)	

Mounted Impact Breakers – continued

Manufacturer	Model no.	Blow energy kg m (ft lb)	Blows per minute	Type of accumulator or spring	Total energy per unit time kg m/min (ft lb/min)	Hydraulic or pneumatic	Weight kg (lb)	Tool shank size (dia) mm (in)
MKT**	RB-2	138 (1,000)	300	none	41,000 (300,000)	P	929 (2,050)	
Montabert, France	BRH125	70 (506)	400-1,000	External nitrogen	70,000 (500,000)	H	272 (600)	70 (2.7)
Montabert, France	250	140 (1,012)	230-600	External nitrogen	84,000 (600,000)	H	550 (1,200)	95 (3.7)
Montabert, France	501	220 (1,590)	350-500	External nitrogen	110,000 (700,000)	H	1,000 (2,200)	114 (4.5)
Montabert, France	1000	450 (3,253)	275-450	External nitrogen	202,000 (1,000,000)	H	1,600 (3,500)	135 (5.3)
Montabert, France	2-96A	69 (500)	175	none	48,000 (350,000)	P	204 (450)	50.8 (2)
Muedon**	450	180 (1,302)	300	none	54,000 (390,000)	P	449 (992)	
National Coal Board, U.K.[e]	Bretby Impact Unit Mark I	85 (600)	180	Internal mechanical spring	15,000 (108,000)	H	450 (1,000)	76 (3)
National Coal Board, U.K.[f]	Bretby Impact Unit Mark II	140 (1,000)	120	Internal mechanical spring	16,800 (120,000)	H	450 (1,000)	76 (3)
NPK**	Dynamax 6000	600 (4,340)	150	none	90,000 (650,000)	P	n.a.	
NPK**	H-11X	387 (2,800)	500		193,000 (1,400,000)	H	1,202 (2,650)	
NPK**	802HB	280 (2,025)	400		112,000 (810,000)	H	729 (1,609)	
NPK**	H-9X	276 (2,000)	500		138,000 (1,000,000)	H	889 (1,962)	
NPK**	Dynamax 2500	270 (1,953)	200	none	53,900 (390,000)	P	749 (1,653)	
NPK**	602HB	210 (1,519)	400		84,000 (600,000)	H	499 (1,102)	
NPK**	H-6X	207 (1,500)	570		110,000 (850,000)	H	600 (1,323)	
NPK**	IPH600	170 (1,230)	310	none	52,000 (380,000)	P	624 (1,376)	
NPK**	IPH400	73 (533)	320	none	23,000 (170,000)	P	405 (893)	
NPK**	H-3X	69 (500)	580		40,000 (290,000)	H	249 (551)	
Oy Tampella Ab TAMROCK Industriel, Finland	HB300	30 20)	1,320	Internal nitrogen	40,000 (290,000)	H	115 (250)	53-63 (2-2.48)
Quincy**	BBH36	13 (100)	1,000		13,000 (100,000)	H	39 (88)	
Quincy**	BBH31	13 (100)	500		6,000 (50,000)	H	29 (66)	
Racine Federated Inc., U.S.A. (formerly manufactured by Worthington Compressors, U.S.A.)	MB-600	[illegible] (500)	600	Bladder	41,000 (300,000)	H	430 (950)	83 (3¼)
Rammer Oy**	S800	120 (886)	840		100,000 (740,000)	H	1,250 (2,756)	

Mounted Impact Breakers – continued

Manufacturer	Model no.	Blow energy kg m (ft lb)	Blows per minute	Type of accumulator or spring	Total energy per unit time kg m/min (ft lb/min)	Hydraulic or pneumatic	Weight kg (lb)	Tool shank size (dia) mm (in)
Roxon**	B-200	132 (959)	560		74,000 (530,000)	H	600 (1,323)	
Roxon**	B-700	299 (2,169)	400		119,000 (860,000)	H	1,000 (2,205)	
Schramm Inc., U.S.A.	B1100	207 (1,500)	500	none	83,000 (600,000)	P	499 (1,100)	101 (4)
Schramm Inc., U.S.A.**	B450	76 (550)	1,100	none	83,000 (600,000)	P	200 (441)	
Shand**		228 (1,650)	180		41,000 (297,000)	H	n.a.	
Shand**	Fluicon	228 (1,650)	200		45,600 (330,000)	H	521 (1,150)	
Stennuick**	BR150	n.a.	200	none	n.a.	P	650 (1,433)	
Theiss**	DCB 2500	268 (1,945)	1,250	none	336,000 (2,430,000)	P	1,059 (2,336)	
Worthington Compressors, U.S.A.[g]	Vanquisher 1000	138 (1,000)	500	none	69,000 (500,000)	P	498 (1,100)	101 (4)
Worthington Compressors, U.S.A [g]	Vanquisher T500	69 (500)	500	none	35,000 (250,000)	P	297 (655)	76 (3)

*Obsolete.

**Data not obtained direct through company but indirectly through other sources.

[a] With heavy-duty side plates.
[b] With silencing muffler.
[c] Discontinued.
[d] Blows per minute may be doubled by operator pressing a button on the operator's panel during operation.

Note: The National Coal Board impact units were designed at the Mining Research and Development Establishment and made to their order:
[e] (Mark I) Partially built in M.R.D.E. Workshops with components made by MacTaggart Scott & Co. Ltd, Scotland.
[f] (Mark II) built by Universal Fisher Engineering Ltd, England.
[g] These models discontinued. Rights for the manufacture of Worthington hydraulic mounted impact breakers sold to Racine Federated Inc. several years ago.

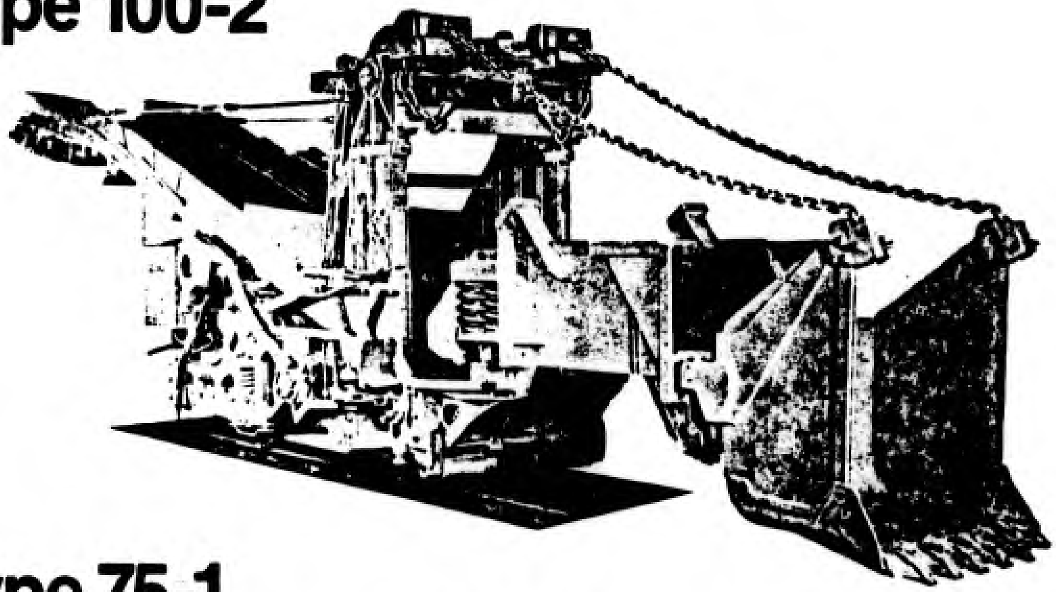
CONWAY MUCK LOADER

Type 100-2 is a rugged, durable machine for heavy mucking in tunnels of 12′ or more in diameter. Its 1½ cubic yard dipper and 42″-wide conveyor belt permit a loading capacity of 243 cubic feet per minute. Power is provided by a 125 hp main motor and a 40 hp conveyor motor. Large shafts, sprockets, bearings and chains assure dependable long life. Track gauge can be from 30″ for 17′ clean-up width to 42″ for 23′ clean-up width.

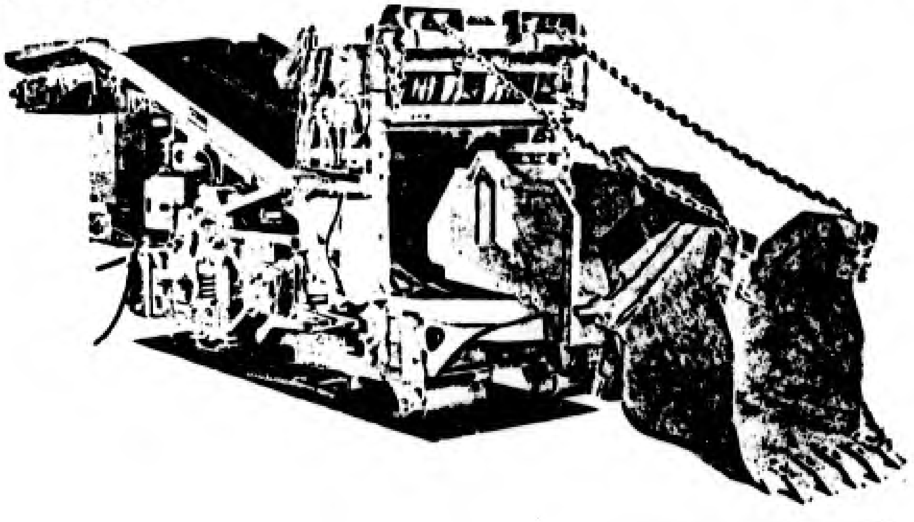
Type 100-1 has a 1¼ cubic yard dipper and 38″-wide conveyor. The main motor is a 100 hp unit; the conveyor is driven by a 30 hp motor. Track gauges can be from 30″ for 14′10″ clean-up width to 42″ for 23′ clean-up width.

Type 75-1 is a medium-size mucker with all the rugged construction features of the full-size units. Dipper capacity is ¾ cubic yard with a 28″-wide conveyor. The main motor is 100 hp; the conveyor motor is 25 hp. Track gauges can be from 24″ to 42″.

Type 100-2



Type 75-1



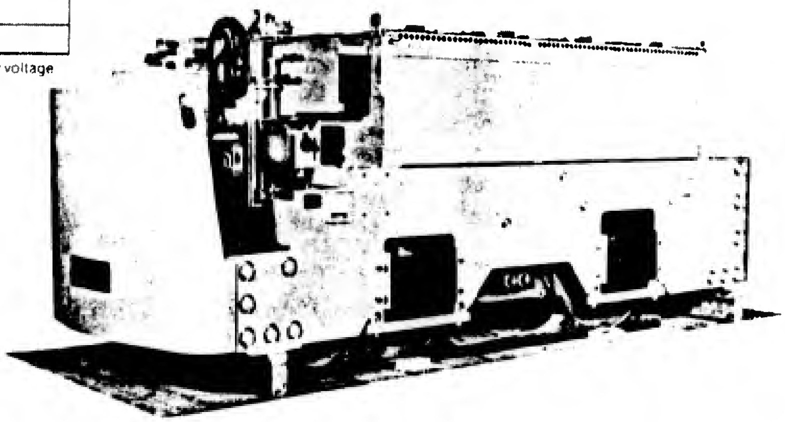
Courtesy of the Goodman Equipment Corp.

Battery or Trolly LOCOMOTIVES

Type 136B

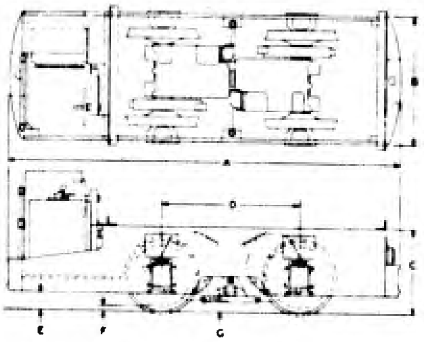
Approximate Operating Weight	20 tons
Tractive Effort One Hour Motor Rating	7,500 Lbs
*Speed at Above Draw Bar Pull	5.8 MPH at 200V
Number of Motors	2
Total HP, Hourly Rating	150 at 250V
Maximum Battery Recommended	200 KWH
Minimum Gauge	36"

*Speed can be varied to suit haulage demands by varying battery voltage



Dimensions

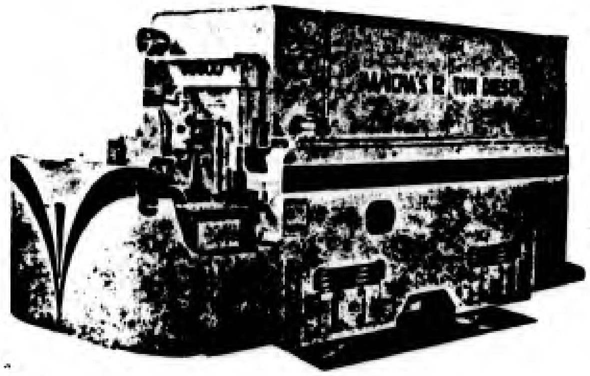
Overall dimensions shown at right are typical but can be varied to meet special operating conditions.



	Type 75D	Type 154	Type 136B
A	12'1"	14'4"	21'9"
B	41½"	54½"	66"
C	30½"	36½"	40"
D	54"	60"	100"
E	6¼"	7½"	8½"
F	1¾"	2¼"	3¼"
G	3"	4½"	8"

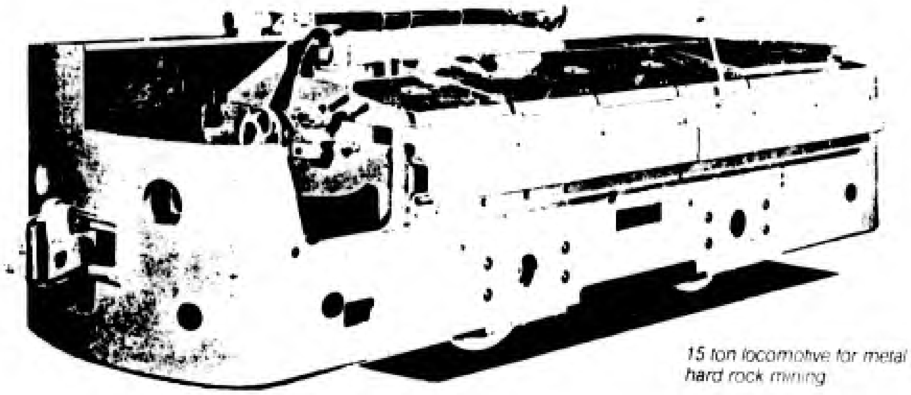
Diesel Powered

	12-Ton	20-Ton
Type	**12CSH**	**20CSH**
T.E.	6000#	10,000#
Speed	10-12 MPH	12-14 MPH
HP	100-146	250
Gauge	30"-36"	30"-36"
	Dimensions	
Length	14'	18'
Width	60"	60"
Height	60"	60"
Wheelbase	60"	87"

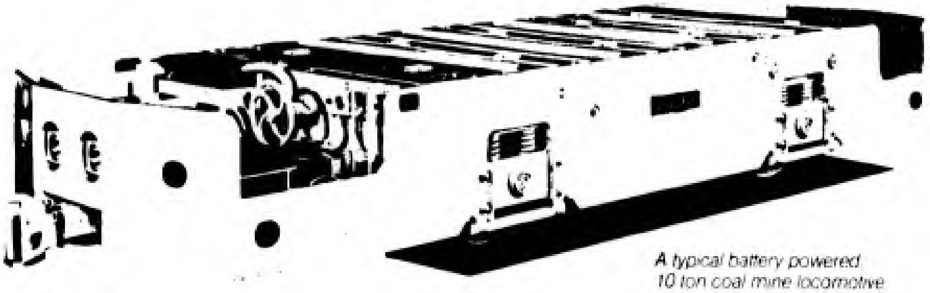


Courtesy of: Goodman Equiptment Corp.

Low Profile Locomotives



15 ton locomotive for metal and hard rock mining



A typical battery powered 10 ton coal mine locomotive

The world famous 8 ton Goodman tunneling locomotive

10 ton PTM, a permissible locomotive, for operation in gassy coal mines

The "Mule" with an open top for carrying parts and materials, typifies Goodman's small utility locomotive concept

Clayton

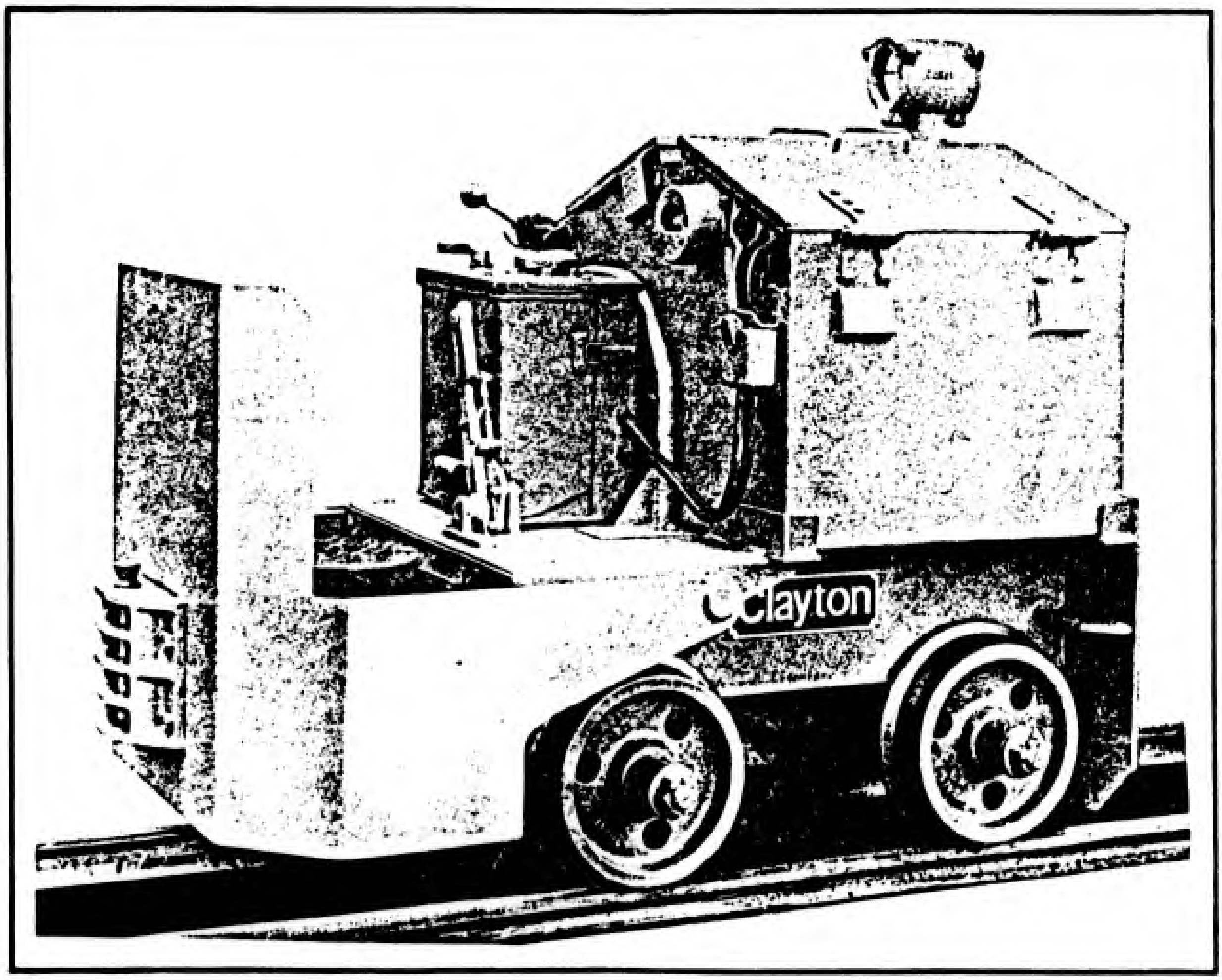
Battery Powered Tunnelling Locomotive

7hp/1¾tonne

(Folding Cab Model)

This locomotive is the most powerful available in its class and is specially designed for use in mines and tunnels.
A single Clayton traction motor coupled to each axle provides positive four-wheel drive, giving 10% greater maximum tractive effort than an equivalent horsepower two-motored locomotive.

Performance	
Tractive effort at one hour rate	300 Kg.
Speed at one hour motor rate	5.7 k.p.h.
Maximum tractive effort (25% adhesion)	437 Kg.



Specification
7hp/1¾ tonne Battery Powered Tunnelling Locomotive

Motor Clayton 7 hp 1 hour rated on 50 volts

Controller Cam contactor type giving four notches of control with dead man's handle arranged to cut traction

Resistance Unbreakable alloy strip type

Battery Traction batteries of 14.5 or 16.7 kwh capacity at the 6 hour rate can be provided

Battery Container Ventilated and weatherproof fitted with heavy duty Colton plug and socket

Transmission Totally enclosed, axle mounted wormdrive gearboxes

Brakes Quick acting lever brake

Wheels and Axles Heat treated, 355 mm (14") dia. wheels. Alloy steel axles

Axleboxes Roller bearing type

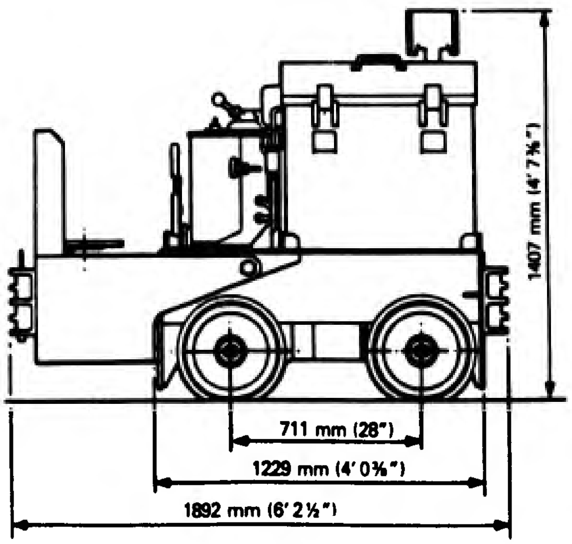
Couplers Link and pin standard

Frame All steel welded construction

Warning Device Brass bell

Optional Extras:
- Electric horn
- Reyrolle plugs and sockets
- Convertible gauge
- Sealed beam headlights
- Discharge indicator
- Battery box rollers
- Charger

Rail gauge	Overall width
457/610 mm (18" – 24") variable	984 mm (3' 2¾")
610/762 mm (24" – 30") variable	984 mm (3' 2¾")
762/914 mm (30" – 36") variable	1137 mm (3' 8¾")



Haulage Capacity Chart

Speed	Tractive Effort	Loads hauled in tonnes on straight track				
k.p.h.	Kg.	Level	1 in 200	1 in 150	1 in 100	1 in 50
0 – 4.8	437	30	21	19.5	16.4	11
6	260	17	12	10.7	9	5.9
8	140	8	5.6	5	4	2.4
10	80	4	2.4	2	1.5	0.5

All the above figures based on an assumed starting and rolling resistance of 14 Kg/tonne

Publication No. T.7503

This specification is accurate at the time of publication. However, with a constant policy of improvement we reserve the right to alter specifications without notice.

Clayton

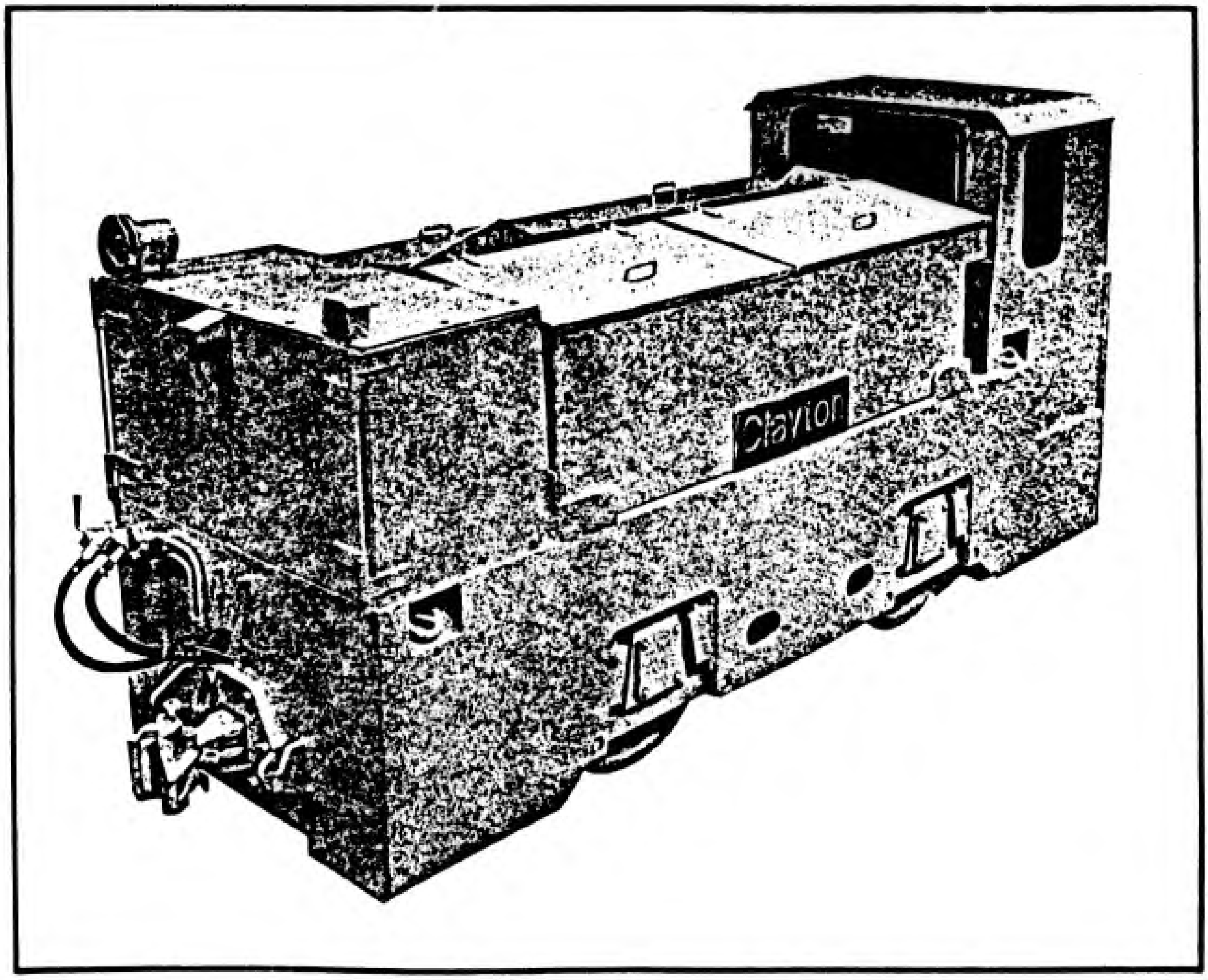
Battery/Trolley Locomotive

120hp/13tonne

This locomotive is of modern design, built for high production haulage on a continuous basis.

Performance

Tractive effort at one hour motor rate	2600 Kg.
Speed at one hour motor rate	11.2 k.p.h.
Maximum tractive effort (25% adhesion)	3250 Kg.



Specification
13 tonne 120 H.P. Battery/Trolley Electric Mining and Tunnelling Locomotive

Motors 2 – 60 hp Clayton 1 hour rated on 250 volts D.C.

Controller By master controller and electro-magnetic contactors giving 5 series, 4 parallel and 6 braking notches

Resistance Edge wound alloy strip type

Transmission Axle hung traction motors, driving through single reduction spur gears

Brakes Straight air brakes and screw operated parking brake

Wheels & Axles Wheels are fitted with renewable steel tyres, pressed on to large diameter axles

Axleboxes Roller bearing type fitted with grease seals

Coupler Link and pin standard

Suspension Bonded rubber to metal chevron springs

Battery 100 cell lead acid type having 104 kwh capacity at the 6 hour rate of discharge

Battery Container Ventilated and weatherproof, lift off type

Torque Arms Steel link fitted with rubber bushes anchored to frame

Frame Robust all welded steel frame

Warning Device Air-operated horn

Headlights Sealed beam type

Sanding Equipment Air operated sanding to all four wheels

Current Collector Slipper type

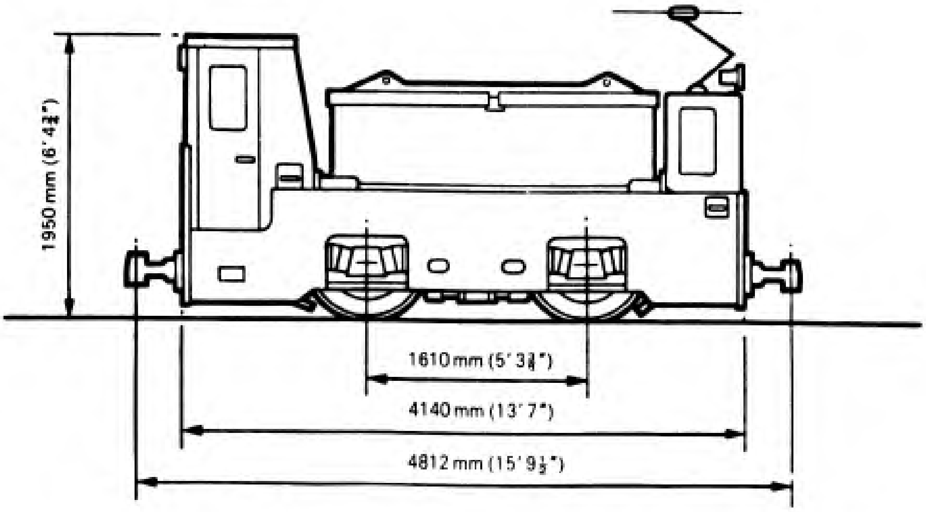
Drivers Cab Totally enclosed

Exterior Finish Safety yellow

Optional Extras:
Multiple working equipment
Battery charger
Pantograph current collector
Automatic couplers

Rail gauge	**Overall width**
762 mm (30")	1370 mm (4' 6")
• 914 mm (36")	1370 mm (4' 6")
•1067 mm (42")	1370 mm (4' 6")

•these locomotives have outside wheels



Haulage Capacity Chart

Speed	Tractive Effort	Loads hauled in tonnes on straight track					
k.p.h.	Kg.	Level	1 in 200	1 in 150	1 in 100	1 in 50	1 in 30
0–9.8	3250	348	219	195	158	99	63
12	1800	187	115	102	82	49	29
16	930	90	53	46	36	19	9
20	550	48	26	22	15	6	–
24	330	23	10	8	4	–	–
28	230	12	3	1	–	..	–

Approval of locomotive for a specific duty must be obtained from Clayton Equipment

Publication No T 7422

Clayton

Main Haulage Diesel Locomotive

100hp/15tonne

Cardan Shaft Drive Locomotive

An outstanding machine, designed for high speed, high production haulage on a continuous basis.

This 15 tonne locomotive can be supplied in weights down to 10 tonne and to suit all rail gauges, 600 mm and above. Where width is a controlling factor this locomotive is supplied as an inside frame model.

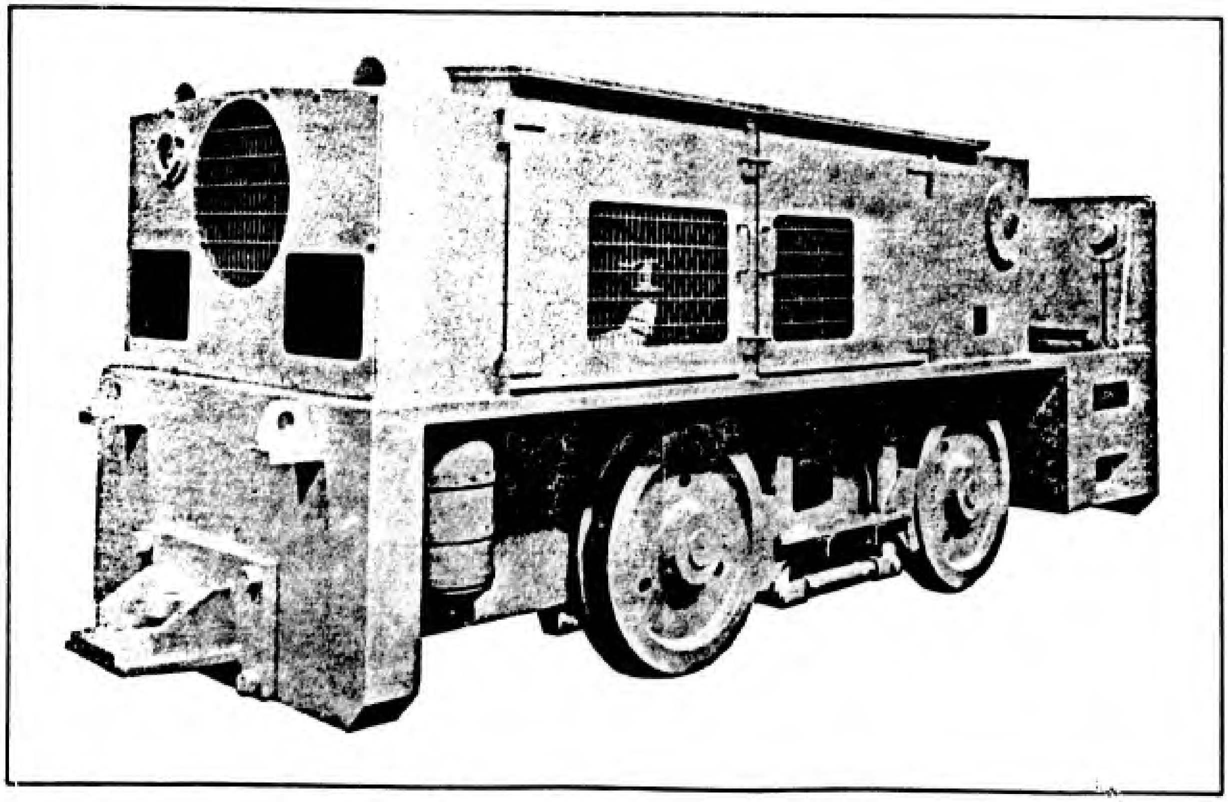
Either a Deutz air-cooled engine or a Perkins water-cooled engine are fitted as standard equipment, but others can be supplied to suit customer's preference.

British Twin Disc Hydrodynamic Series 400 torque converter, incorporating constant mesh gears and hydraulically operated clutches for forward and reverse, transmits the drive via Cardan shafts to bevel and spur gear axle-mounted gearboxes.

Air brakes are standard fitting.

Performance

Maximum tractive effort (25% adhesion)	3750 Kg.
Maximum speed	16 k.p.h.



Specification
Main Haulage Diesel Locomotive 100 h.p./15 tonne

Weight 15 tonne (other weights available)

Engine Deutz air cooled, type F6L-714 rated 100 h p at 2300 r p m.
(alternative engines available on request)

Transmission Single stage torque converter
Constant mesh spurgear with multiplate clutches

Axle Mounted Gearboxes Clayton bevel and spur, totally enclosed traction type

Brakes Straight air service brake. Screw operated parking brake

Wheels 762 mm dia solid cast steel

Suspension Rubber chevron type

Axleboxes Roller bearing type

Frame Heavy steel plate, all welded

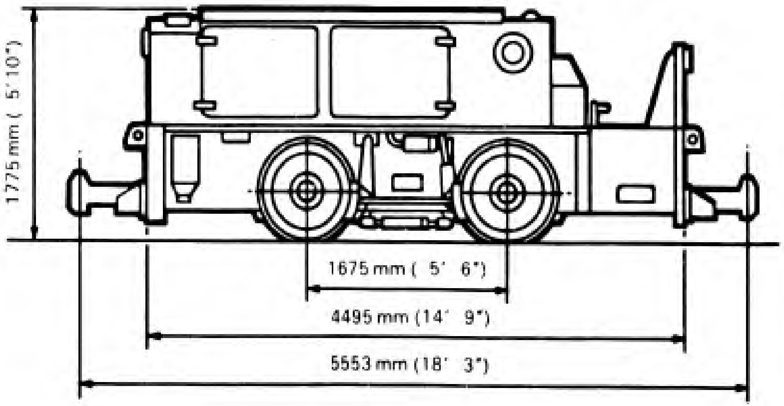
Coupler (Standard). Three pocket link and pin type

Painting Safety Yellow

Standard Equipment:
- Warning Horn
- Headlights
- Ammeter
- Automatic shut down for low oil pressure and high temperature
- Speedometer

Optional Extras:
- Oxy-catalyst exhaust gas conditioner
- Air operated sanding
- Totally enclosed cab
- Two speed transmission
- Automatic couplers
- Multiple working equipment
- Engine hour meter

Rail Gauge	**Overall Width**
600 mm (24") to 1067 mm (3'6")	1420 mm (4'8")



Haulage Capacity Chart

Speed	**Tractive Effort**	**Loads hauled in tonnes on straight track**				
k.p.h.	Kg.	Level	1 in 200	1 in 150	1 in 100	1 in 50
0–4	3750	402	253	224	182	114
6	3000	318	200	177	144	88
8	2625	277	172	153	123	75
10	2300	240	150	132	106	64
12	1275	127	76	66	52	29
14	625	54	30	25	18	7

All the above figures are based on a starting and rolling resistance of 9kg/Tonne

Publication No. T7613

Clayton

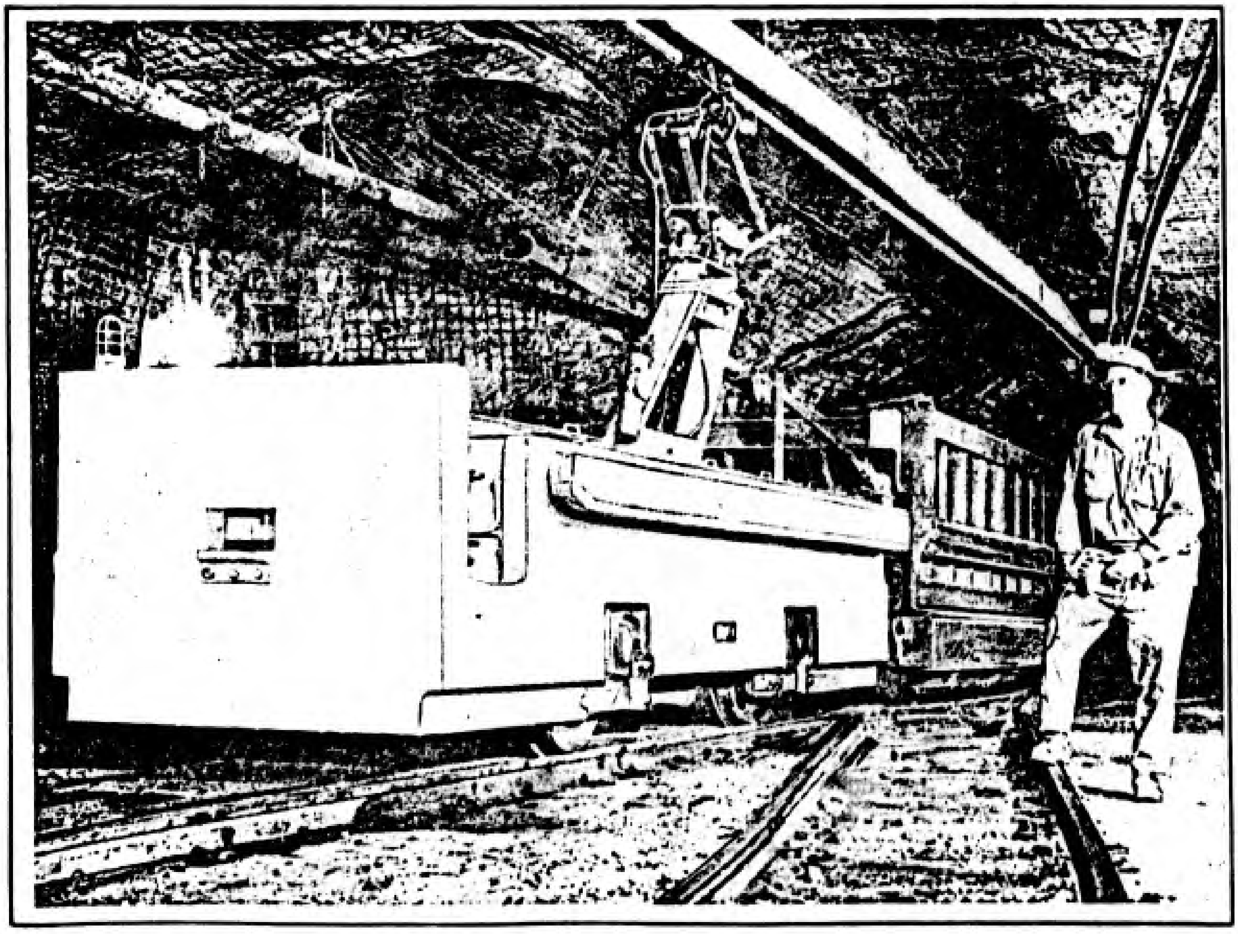
Main Haulage Trolley Locomotive

244hp/20tonne

This locomotive is of modern design, built for high production haulage on a continuous basis.

Performance

Tractive effort at one hour motor rate	4,540 Kg.
Speed at one hour motor rate	14.4 k.p.h.
Maximum tractive effort (25% adhesion)	5,000 Kg.



Specification
20 tonne 244 h.p. Trolley Electric Mining and Tunnelling Locomotive

Motors 2 – 122 h p 1 hour rated on 250 volts D C

Controller By master controller and electro magnetic contactors giving series and parallel control

Resistance Edge wound alloy strip type

Transmission Axle hung traction motors, driving through single reduction spur gears

Brakes Straight air brakes and screw operated parking brake

Wheels and Axles Wheels are fitted with renewable steel tyres pressed on to large diameter axles

Axleboxes Roller bearing type fitted with grease seals

Coupler Link and pin standard

Suspension Bonded rubber to metal chevron springs

Torque Arms Steel link fitted with rubber bushes anchored to frame

Frame Robust all welded steel frame

Warning Device Air operated horn

Headlights Sealed beam type

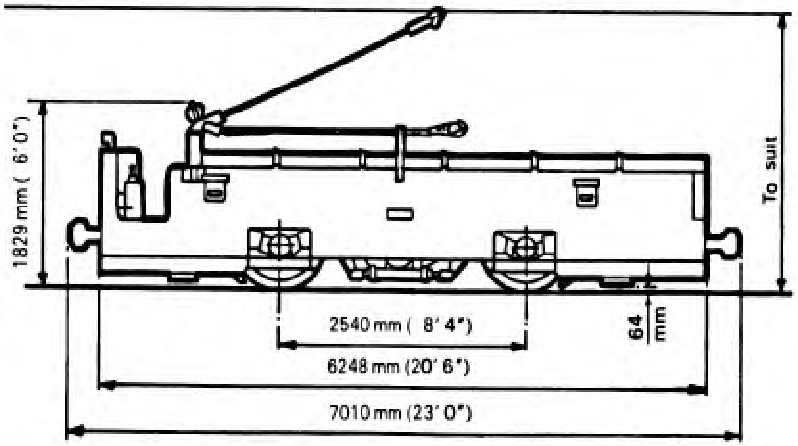
Sanding Equipment Air operated sanding to all four wheels

Current Collector Slipper type

Exterior Finish Safety yellow

Optional Extras:
Remote control radio or auxiliary overhead wire
Train brakes
Pantograph current collector
Automatic couplers

Rail Gauge	**Overall Width**
914 mm (36")	1600 mm (5' 3")
1067 mm (42")	1753 mm (5' 9")



Haulage Capacity Chart

Speed	Tractive Effort	Loads hauled in tonnes on straight track				
k.p.h.	Kg.	Level	1 in 200	1 in 150	1 in 100	1 in 50
0–13 8	5000	535	336	298	243	152
16	3240	340	221	186	150	92
18	2270	233	142	125	100	58
20	1825	183	120	96	76	43
24	1140	107	62	53	40	19
30	620	49	24	20	12	1

All the above figures are based on a starting and rolling resistance of 9kg/Tonne.

Publication No T7611

SELECTING RAIL AND CROSS TIE SPACING

Recommended Maximum Load, One Wheel, in Pounds[2]

Weight of rail,* lb/yd	Tie spacing, in.			
	24	30	36	42
8	800	600	500	400
12	1,800	1,300	1,100	1,000
16	2,700	2,200	1,800	1,500
20	3,800	3,100	2,500	2,100
25	4,700	3,800	3,100	2,700
30	6,700	5,400	4,500	3,900
35	8,100	6,400	5,400	4,600
40	9,700	7,700	6,400	5,500
45	11,300	9,100	7,600	6,500
50	13,300	10,600	8,900	7,600
55	15,300	12,300	10,200	8,800
60	17,700	14,100	11,600	10,000

* Standard lengths: 30 ft for weights up to 45 lb/yd.
33 ft for 50 lb/yd or heavier.

Dimensions and Weights of Light Rail, ASCE Section[2]

Weight of rail, lb/yd	Height and width of base, in.	Width of head, in.	Section modulus	Weight of rail for 100 ft of track, lb	Weight 1 pr. splice bars and 4 bolts, lb	Size of bolt, in.	Size of spike, in.
8	1 9/16	13/16	0.32	533	2.45	3/8 × 1 1/2	3/8 × 2 1/2
12	2	1	0.63	800	4.24	1/2 × 1 3/4	3/8 × 2 1/2
16	2 3/8	1 11/64	1.01	1,067	5.16	1/2 × 1 3/4	3/8 × 3
20	2 5/8	1 11/32	1.43	1,333	5.69	1/2 × 2	3/8 × 3 1/2
25	2 3/4	1 1/2	1.77	1,667	6.56	1/2 × 2 1/4	1/2 × 4
30	3 1/8	1 11/16	2.53	2,000	8.99	5/8 × 2 1/2	1/2 × 4
35	3 5/16	1 3/4	3.02	2,333	9.26	5/8 × 2 1/2	1/2 × 4 1/2
40	3 1/2	1 7/8	3.62	2,667	14.33	3/4 × 3	1/2 × 5
45	3 11/16	2	4.25	3,000	16.71	3/4 × 3	9/16 × 5 1/2
50	3 7/8	2 1/8	4.98	3,333	19.17	3/4 × 3 1/4	9/16 × 5 1/2
55	4 1/16	2 1/4	5.75	3,667	31.81	3/4 × 3 1/2	9/16 × 5 1/2
60	4 1/4	2 3/8	6.62	4,000	35.33	3/4 × 3 1/2	9/16 × 5 1/2

Parker 71, After Mayo

Tunnel Boring Machine (TBM) Manufacturers

Atlas Copco, Inc.
29125 Hall Street
Solon, OH 44139

Calweld
(Div. of Smith International Pty Ltd)
9206 S. Sorenson Ave.
Sante Fe Springs, CA 90670
TEL: 213-723-0881

Mannesman Demag
Wolfgang-Reuter-Platz
D-4100 Duisburg
Federal Republic of Germany
TEL: 0203-6051

Dresser Industries
(Mining Services & Equipment Div.)
Box 24647
Dallas, TX 75224

Greenside/McAlpine

Bade & Co. GmbH
(Bade & Theelen GmbH)
D-3160 LEHRTE GERMANY
TEL: 5132-53081

Habegger Ltd

Hughs Tool Co.
Mining and Construction Equipment Div.
P. O. Box 2539
Houston, TX 77001

Wirth Maschinen-und Bohrgerate-Fabrik GmbH
P. O. Box 1327/1329
D-5140 Erkelenzl, West Germany
TELEX: 8-329-860

Jarva Inc.
29125 Hall St.
Solon, OH 44139
TEL: 216-248-0166

Komatsu
(Komatsu-Robbins)
555 California St.
San Francisco, CA 94104
TEL: 910-372-7889

Fried Krupp GmbH
(Krupp Widia)
Postfach 102161
D-4300 ESSEN 1
West Germany
TELEX: 085-718-0

Mitsubishi Heavy Industries Ltd
5-1 Marunouchi 2 chome
chiyoda-ku
P. O. Box 10 Tokyo Central
Tokyo, Japan
TEL: 03-212-3111

National Coal Board (UK)

Robert L. Priestley Ltd.
20 Grosuenor Cardens
London Swiwodr, England
TEL: 01-730-8958

The Robbins Co.
7615 South 212th St.
Kent, WA 98031
TEL: 206-872-0500

Tunnel Shield Manufacturers

Bade & Theelen GMBH
D3160 Lehrte, West Germany
TEL: 5132-53081

Hitachi Zosen
1-1-1, Hitotsubashi
Chiyoda-Ku
Tokyo 100, Japan

Markham & Co. Limited
Broad Oaks Works
Chesterfield, Derbyshire
S41 ODS, England
TEL: 0246-76121

Milwaukee Boiler Manufacturing Co.
1101 S 41st
Milwaukee, WI 53215
TEL: 414-645-0068

R. Schafer & Urbach GMBH
PO Box 1605
D-4030 Ratingen, West Germany
TEL: 02102-42018

Stelmo International
Ashford, Kent
England TN27 OEJ
TEL: 023-371-2395

Zokor
1470 North Farnsworth Ave
Aurora, IL 60507
TEL: 312-851-8000

Mechanized Shield Machine Manufacturers

Markham & Company Limited, U.K.
Sir Robert McAlpine & Sons Ltd, U.K.*
Robert L. Priestley Ltd., U.K.
Jarva Inc., U.S.A.
Kinnear Moodie & Company Ltd., U.K.*
Bade & Theelen GmbH, West Germany
Tunnelling Equipment (London) Ltd., U.K.
Calweld Inc. - Division of Smith International, U.S.A.*
W. Lawrence & Sons (London) Ltd., U.K.
Westfalia Lunen, West Germany
Arthur Foster, U.K.*
Lovat Tunnel Equipment Inc., Ontario
M&H Tunnel Equipment, U.S.A.*
Machinoexport U.S.S.R.
Aubrey Watson Ltd., U.K.*
Zokor International Ltd., U.S.A.
Decker Mnf. Co., U.S.A.
Memco, U.S.A.*
Robbins Company, U.S.A.
Elgood Mayo Corp., U.K.
Milwaukee Boiler Manufacturing Co., U.S.A.
Stelmo Ltd., U.K.
Marcon Ltd., U.K.
Martin Herrenknecht GmbH, West Germany
Komatsu Ltd., Japan
Nihon Koki Co., Ltd., Japan
Mitsubishi Heavy Industries Ltd., Japan
Mitsui Engineering & Shipbuilding Co., Ltd., Japan
Hitachi Construction Machinery Company, Ltd., Japan
Ishikawajima-Harima Heavy Industries Co. Ltd., Japan
Hitachi Shipbuilding & Engineering Co., Ltd., Japan
Kawasaki Heavy Industries Co. Ltd., Japan
Iseki Poly-Tech., Japan
R. Schafer & Urbach GmbH, West Germany

* These companies have either stopped manufacturing soft-ground machines or have ceased trading.

Slurry and Earth Pressure Balanced Machine Manufacturers

Markham & Co. Ltd., U.K.
Robert L. Priestley Ltd., U.K.
Orenstein & Koppel, AG, West Germany
Gardner Engineering Corp., U.S.A.*
Wayss & Freytag, AK, West Germany
Komatsu Ltd., Japan
Mitsubishi Heavy Industries Ltd., Japan
Mitsui Engineering & Shipbuilding Co. Ltd., Japan
Hitachi Construction Machinery Co. Ltd.
Ishikawajima-Harima Heavy Industries Co., Ltd., Japan
Hitachi Shipbuilding & Engineering Co. Ltd., Japan
Kawasaki Heavy Industries Co. Ltd., Japan
Iseki Poly Tech., Japan

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* These companies have either stopped manufacturing soft-ground machines or have ceased trading.

Partial Face Machine Manufacturers

AEC Incorporated
PO Box 106
531 E. Marylyn Ave.
State College, PA 16801
TEL: 814-238-1114

Alpine
(Vost-Alpine)
Floragasse 7
A-1040
Vienna, Austria
TEL: 0222-654711

Anderson Mavor
R.D. #1 Box 167C
Anderson Road
Evans City, PA 16033
TEL: 412-452-4400

Anderson Strathclyde Ltd

Atlas Copco
29125 Hall Street
Solan, OH 44139
TEL: 216-248-0166

Demag AG
(Mannesman Demag Bergwerktechnik)
Wolfgang-Reuter-Platz,
D-4100 Duisburg
Federal Republic of West Germany
TEL: 0203-6051

The Dosco Corporation
1020 N. Eisenhower Drive
Beckley, WV 25801
TEL: 304-253-8384

Eickhoff Maschinenfabric
Eisengiesserle mbH,
Heenschedtstrasse 176,
D-4630 Bochum 1, Germany
TELEX: 08 25 804

Ingersol Rand
PO Box 4235
Grand Central Station
New York, NY 10017
TEL: 212-953-0178

Memco, USA

Pamet

Paurat GmbH
4223 Voerde 2.
Nordstrasse 73
West Germany
TEL: 281-4580

The Robbins Company
7615 South 212th St.
Kent, WA 98031
TEL: 206-872-0500

Salzgitter Maschinen Und
Anlagen AG,
Pastfach 51 1640,
3320 Salzgitter 51,
Austria
TELEX: 954-445-SMAGD

Thyssen Limited
Bynea, Llanelli, Dyfed
5A149SU England
TEL: 05542-2244

Voest-Alpine
Lincoln Building
60 East 42nd Street
New York, NY 10165
TEL: 212-661-1060

Westfalia Lunen
D-4670 Lunen
Federal Republic of
West Germany
TEL: 02306-1071

Zokor
1470 North Farnsworth
Avenue
Aurora, IL 60507

Pneumatic and Hydraulic Drill Manufacturers

Linden-Allmak AB
Lloyd Moore
Raise Equipment
4211 N. Milwaukee St.
Denver, CO 80216
TEL: 303-321-3087

Atlas Copco
Thomas M. Skodak
Sr. Product Specialist, Mining
Atlas Copco, Inc.
70 Demarest Dr.
Wayne, NJ 07470
TEL: 201-696-0554

Secoma
Bernard Y. Saltiel
Technical Sales Engineer
Secoma America
PO Box 1211
Salt Lake City, UT 84110
TEL: 801-532-3400

Gardner-Denver
Don A. Rohrenbach
Product Manager
Gardner-Denver Co.
1727 E. 39th Ave.
Denver, CO 80205

Ingersoll-Rand
Kenneth S. Moffitt
General Manager
Ingersoll-Rand Co.
942 Memorial Pkwy.
Phillipsburg, NJ 08865
TEL: 201-859-7432

NYA Stromnes AB,
Tunavagen 279,
S-781 35 Borlange,
Sweden
TELEX: 740 36 STROMNES

Jarvis Clark/Montabert
John H. Clark
President
Jarvis Clark, Inc.
PO Box 3400
Golden, CO 80401
TEL: 303-232-7079

Joy
George A. Hibbard
Chief Engineer
Joy Manufacturing Co.
River Rd.
Claremont, NH 03743
TEL: 603-543-3131

LeRoi
A. Burt Thut
Sales Manager Drills
LeRoi Division
Dresser Industries Inc.
N. Main Ave. & Russell Rd.
Sidney, OH 45365
TEL: 513-492-1171

SIG
Andrea Kolb
Department WF-P
Sig Swiss Industrial Co.
CH-8212 Neuhausen Rhine Falls
Switzerland 053-81555

Tamrock
Pentti Ranta-Aho
President
Tamrock, Inc.
PO Box 16385
Denver, CO 80216
TEL: 303-893-5308

Perard Torque Tension Ltd,
Brittain Drive
Codnor Gate Indusrial Estate, Ripley,
Derby DE5 3QB, UK
TELEX: 377425

Macol Shaft Sinking Ltd.
107 Dale Road, Mat Lock,
DERBY DERBY DE4 3LU, UK

EIMCO Mining Machinery International
3000 Sand Hill Road,
Menlo Park, CA 94025, USA
TELEX: 415 854 2000

Turmag GB Ltd.
Falcon Works
203 Outgang Lane, Dinnington,
Sheffield S31 7QY, UK
TELEX: 547401

Locomotive Manufacturers

Goodman Equipment Corporation
4038 S Halsted
Chicago, IL 60609
TEL: 312-927-7420

Balco Inc. (A Rubicon Subsidiary)
PO Box 56-TR
Blairsville, PA 15717
TEL: 412-459-6814

Earle, James M. Company
Box 0233
114 Maintoloking Rd
Mantoloking, NJ 08738
TEL: 201-477-7002

Clayton Equipment
Hatton, Derby D56 56B
England
TEL: 0283-812382

Plymouth Locomotive Division (Pennbro. Corp.)
PO Box 130-T
Brookville, PA 15825
TEL: 814-849-7321

Sig Swiss Industrial Company
CH-8212 Nevhausen Rhine Falls
Switzerland
TEL: 053-81555

Brookville Locomotive Division Pennbro. Corp.
PO Box 130-T
Brookville, PA 15825
TEL: 814-849-7321

Ageve
P. O. Box 655, S-801 27
Cavle, Sweden
TEL: 4626115890

Mucking Car Manufacturers

ACF Industries, Inc.
AMCAR Div., Clark & Main Sts.
1114 Avenue of the Americas/Grace Bldg.

Card Corp.
PO Box 117
Denver, CO 80201
TEL: 303-922-7511

Difco, Inc.
1511 N Main St.
Findlay, OH 45840
TEL: 419-422-0525

Goodman Equipment
4038 S Halsted
Chicago, IL 60609
TEL: 312-927-7420

Watt Car & Wheel Co.
1862 Watt Ave.
Barnesville, OH 43713
TEL: 614-425-1924

The Titon Manufacturing Co. Pty Ltd.
Woodstock St.
Mayfield NSW 2304
Australia
TELEX: 28074

Symons Corporation
200 E Touhy Ave.
Des Plaines, IL
TELEX: 28-2487 Symons DSP

Karl H. Muhlhauser
P. O. Box 3360
6120 Michelstadt/Odwl
West Germany
TELEX: 4191623

Track Manufacturers

Safetran Systems Corporation
505W Ornsby
Louisville, KY 40203
TEL: 502-361-1691

Atlantic Track and Turnout Company
270-T Broad St.
Bloomfield, NJ 07003
TEL: 201-748-5885

Abex Corp., Railroad Group
Vally Rd.
Mahwah, NJ 07430
TEL: 201-529-3450

Midwest Steel
736C E. Main St.
Pomeroy, OH 45769
TEL: 614-992-3285

Marmon Transmotive, A Division of Marmon Group Inc.
PO Box 1511-T
Knoxville, TN
TEL: 615-525-6224

Delta Construction, Ltd
Wylds Road, Bridgwater,
Somerset TA6 4BH, UK
TELEX: 46353

Rubber-Tired and Crawler-Mounted Mucking Equipment Manufacturers

ASTRA
Special Vehicles Construction
Piacenza, Italy
TEL: 0523-62010

KIRUNA TRUCK
Mining Transportation Co. AB
Box 999 S-981 01
Kiruna, Sweden
TEL: 0980/18620

DJB ENGINEERING LIMITED
Peterlee, Co
Durham, England SR82HX
TEL: 0783-863333

EIMCO (Great Britain) LIMITED
Box 1211
Salt Lake City, UT 84110
TEL: 1-800-453-3207

MINDEV
Mining Development Limited
Horwich, Bolton BL65HN
Lancashire, England
TEL: 0204-685212

M. A. N.
Untermehmensbereich GHH Sterkrade
PO Box 110240
D-4200 Oberhausen 11, West Germany
TEL: 0208-692-2

KAELBLE-GMEINDER
Carl Kaelble GMbH
PO Box 1320
D-7150 Backnang, West Germany
TELEX: 724 428

PECLAIN
60330 Le Plessis
Belleville, France

RIMPULL
PO Box 748
Olathe, Kansas 66061
TEL: 913-782-4000

Caterpillar
100 N.E. Adams
Peoria, IL 61629
TEL: 309-675-1000

International Harvester Co.
600 Woodfield, Dept 923
Schaumberg, IL 60196
TEL: 312-884-3000

John Deere
Deere & Co.
Moline, IL 61265
TEL: 309-752-8000

Allis Chalmer
Box 521
Topeka, KS 66601
TEL: 913-354-8401

Broyt A/S
Brodr. Soyland
N-4341 Bryne
Norway

Schopf Maschinen bau GmbH
Postfach 750360,
7000 Stuttart 75
West Germany
TELEX: 725 6651

Toro
Perusyhtyma oy Ara
P. O. Box 434, 20101 Turku 10,
TEL: 357-21-383111

Minder Ltd
Horwich, Bolton
Lancashire BL6 5HN, UK
TELEX: 63365

ERLAU AG
P. O. Box 1226
D-7080 Aalen
West Germany
TEL: 07361-595-240

SCHOPF MACHINEBAU GMbH
PO Box 750360
D-7000, Stuttgart 75, West Germany
TEL: 0711-341087

WALDON INCORPORATED
Fairview, Oklahoma 73737
TEL: 405-227-3711

WAGNER MINING EQUIPMENT CO.
PO Box 20307
4424 NE 158th Ave.
Portland, OR 97220
TEL: 503-255-2863

APPENDIX B: LIST OF CONTACTS

The following companies were contacted to solicit information on equipment specifications, new developments, and future trends in the manufacture of tunnel and shaft construction equipment. Their assistance is gratefully acknowledged.

Clayton Equipment
Hatton, Derby D56 56B
England
TEL: 0283-812382

Difco Incorporated
1511 North Main Street
Findlay, OH 45840
TEL: 419-422-0525

Atlas Car and Manufacturers
110-1144 Ivan Road
Cleveland, OH 44110
TEL: 216-451-7033

Robert L. Priestley
20 Grosrenor Cardens
London 5W1WODY
TEL: 01-730-8958

Markham and Company
Chesterfield, Derbyshire S410DS
England
TEL: (0246) 76121

Akkerman Manufacturers Company
Incorporated
Browndale, MN 55918
TEL: 507-567-2285

Joy Manufacturing Company
999 Plaza Drive
Schaumburg, IL
TEL: 312-884-7750

Cardner Denver
1800 Cardner Expressway
Quincy, IL 62301

Padley and Venables
Cally Whitt Lane, Dronfield
Sheffield S1B 6XT
England
TEL: 0246-413301

Goodman Equipment
4038 South Halsted
Chicago, IL 60609
TEL: 312-927-7420

Card Corporation
PO Box 117
Denver, CO 80201
TEL: 303-922-7511

Jarva Incorporated
29125 Hall Street
Salon, OH 44139
TEL: 216-248-0166

Zokor
1470 North Farnsworth Avenue
Aurora, IL 60507
TEL: 312-851-8000

Milwaukee Boiler Manufacturers
101 South 41st Street
Milwaukee, WI 53215
TEL: 414-645-0068

Ingersoll-Rand
PO Box 4235
Grand Central Station
New York, NY 10017
TEL: 212-953-0178

Atlas Copco, Incorporated
72 Demarest Drive
Wayne, NJ 07470
TEL: 201-696-0554

Tam Rock Incorporated
PO Box 16385
Denver, CO 80216
TEL: 303-289-4141

Stelmo International
Westwill Leacon, Charing
Ashford, Kent TN27 OEJ
England
TEL: 023-371-2395

Anglo Scandia Drilling, Equipment
2 Foxwood Road
Sheepbidge Estate
Chesterfield, Derbyshire, England
TEL: 0246-451096

Allied Steel and Tractor Company
5800 Harper Road
Solon, OH 44139
TEL: 216-248-2600

Thyssen
1114 Avenue, Dept. TR
New York, NY 10036
TEL: 212-764-0588

Voest-Alpine International
Corporation
60-A E. 42nd Street
New York, NY 10017
TEL: 212-661-1060

The Robbins Company
Kent, WA

Flow Industries
Kent, WA

Anderson-Strathchyde
47 Broad Street
Glasgow G40 2QW Scotland
TEL: 041-554-1800

AEC Incorporated
531 Easy Marylyn Avenue
State College, PA 16801
TEL: 814-238-1114

Dosco Overseas Engineering
1020 N. Eisenhower Drive
Beckley, WV 25801
TEL: 304-253-8384

APPENDIX C: COST AND PERFORMANCE DATA FOR SELECTED TUNNELS

APPENDIX C

COST AND PERFORMANCE DATA FOR SELECTED TUNNELS

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Cost Summary for Drill and Blast Tunnels

1. Mayo et al. (1968) gave costs per foot for several tunnels driven by drill and blast methods through differing geological conditions. Total excavation costs per foot of tunnel were given in 1967 dollars and could be updated to 1982 dollars using the Bureau of Labor Statistics (BLS) or Engineering News Record (ENR) price indices. However, these costs show relative trends as they are listed. Phase costs were originally published in 1959 as Appendix C of Bulletin 78 of the California State Department of Water Resources. Costs were updated to 1967 by Mayo et al.

2. For tunnels constructed in dry stratified or schistose rock using D&B excavation, costs for small tunnels (9-13 ft) ranged from $303 to $380/ft. Costs for medium size tunnels (14-18 ft) ranged from $391 to $529/ft. Costs for large tunnels (19-24 ft) ranged from $560 to $714/ft.

3. For tunnels driven through dry massive rock to moderately jointed rock using drill and blast excavation costs ranged from $343 to $440/ft. Costs for medium size (14-18 ft) tunnels ranged from $454 to $612/ft. Large tunnels (19-24 ft) ranged from $648 to $813/ft.

4. Corresponding costs for small, medium, and large tunnels driven through dry, moderately blocky and seamy rock using the DBM were $313 to $398/ft, $412 to $558/ft, and $592 to $754/ft.

5. Drill and blast tunnels in dry, very blocky and seamy rock were listed from $330 to $405/ft for small tunnels, $415 to $584/ft for medium tunnels, and $617 to $793/ft for large tunnels. For all the above cases, costs per foot of tunnel within these size ranges do not vary over wide ranges ($303 to $440/ft for small tunnels, $391 to $612/ft for medium tunnels, and $560 to $813/ft for large tunnels).

6. However, for dry headings in completely crushed or unconsolidated sediments these costs increased significantly. Costs were $470 to $654/ft for small tunnels, $687 to $1043/ft for medium size tunnels, and $1141 to $1813/ft for large tunnels.

7. When groundwater inflows must be dealt with, costs go up even more. Wet headings in competent rock constructed by drill and blast methods ranged from $893 to $1042/ft for total excavation costs in small (9-13 ft) tunnels. Corresponding costs were $1106 to $1640/ft for medium tunnels, and $1684 to $2411/ft for large tunnels (19-24 ft).

8. Wet headings in crushed rock or unconsolidated sediments present formidable tunneling conditions and, consequently, formidable costs. The costs given below are in 1967 dollars, in keeping with the previously cited cases. Costs ranged from $1377 to $1633/ft for small tunnels, $1861 to $2661/ft for medium tunnels, and $3263 to $5812/ft for large tunnels. Construction of tunnels under these conditions normally requires fully shielded, hand-mining methods in conjunction with compressed air, which significantly increases costs and decreases productivity. If a factor of 2.5 is assumed to bring these 1967 dollars up to 1982, the costs tabulated below would give the range of costs per foot of tunnel for various size tunnels and cited conditions. This correction does not take into account technological changes during the last quarter century.

Tunnels constructed by drill and blast excavation	Range of excavation costs per foot for small, medium, and large tunnels (1967 dollars times 2.5)		
	Small (9-13 ft diam)	Medium (14-18 ft diam)	Large (19-24 ft diam)
Dry, stratified or schistose rock	$758-$950	$978	$1400-$1785
Dry, massive to moderately jointed rock	$858-$1100	$1135-$1530	$1620-$2033
Dry, moderately blocky or seamy rock	$783-$995	$1030-$1395	$1480-$1885
Dry, very blocky and seamy rock	$825-$1013	$1038-$1460	$1543-$1983
Dry headings in completely crushed or unconsolidated sediments	$1175-$1635	$1718-$2608	$2853-$4533
Wet headings in competent rock	$2233-$2605	$2765-$4100	$4210-$6028
Wet headings in crushed rock or unconsolidated sediments	$3443-$4084	$4654-$6653	$8158-$14530

Note: No special emphasis should be given to the factor of 2.5 to update costs from 1967 to present dollars. The actual aggregate inflation factor may be 20 percent or so higher and would vary for different reasons but the same relative cost trends would still be seen and this is the important point, i.e., relative costs for different conditions and sizes of tunnels.

Cost and Performance Data, Case Histories from U. S. Army
Corps of Engineers EM 1110-2-2901

LINE NO.	CONSTRUCTED BY C. OF E. DISTRICT	PROJECT & APPROX. DATE DESIGN AND CONSTRUCTION	FINISHED DIAMETER	TUNNEL TYPE	TUNNEL SECTION	TEMP. SUPPORTS	SUPPORT SPACING	MAX. DESIGN HEAD	CONC. LINING THICK.	fc' P.S.I.	LONG. STEEL	HOOP STEEL	AREA OF STEEL/FT.
1	Omaha	Oahe (1958 - 59) S. Dak.	7'	Drain	Circular	5I 5.7	4'	0	0'-9"	3000	#6 @ 18	#6 @ 12 OF #11 @ 18 IF	
2	Omaha	Oahe (1958 - 59) S. Dak.	8'	Unwatering	Circular	5I 10	4'	0	1'-4"	3000		#9 @ 12 OF #9 @ 9 IF	
3	Omaha	Oahe Downstream (1953 - 57) S. Dak.	18'-3'	Flood Control (Pressure)	Circular	8WF24	4'	235'	2'-3'	3000	#11 @ 18 #11 @ 10	#11 @ 12 #11 @ 10	
4	Omaha	Oahe Upstream (1953 - 57) S. Dak.	19'-9"	Flood Control (Non-Pressure)	Circular	8WF20	4'	235'	2'-3'	3000	#11 @ 18 #11 @ 10	#11 @ 18	
5	Omaha	Oahe (1953 - 57) S. Dak.	24'	Power (Upstream of Dam Axis)	Circular	8WF31	3'	210'	2'-6"	3000	#9 @ 12	#11 @ 9 OF #11 @ 9 IF	
6	Omaha	Oahe (1958 - 62) S. Dak.	24'	Power (Downstream of Dam Axis)	Circular	8WF31	3'	272'	2'-6"	3000	#9 @ 12	#11 @ 12 OF #18 @ 12 IF	
7	Huntington	N. Fork Pound (1963-64) Virginia	7' 6"	Diversion & F. C.	Horseshoe			87.5'	1'-8" Walls 1'-6" Base	3500		#5 @ 12	
8	Baltimore	East Br. Clarion (1948) Penn.	10'		Circular	6WF16	3'-1"	154'	2'-0"	6200	None	None	
9	Baltimore	East Branch Dam (1948) Penn.	10'	Diversion & Flood Control	Circular	None	None	152.5'	2'-0"	6200	None	None	None
10	Albuquerque	Conchas (1938) New Mex.	11'		Circular	7/64" Liner Plates	Continuous	83'	1'-6"		18-1" Sq. OF 18-1" Sq. IF	1" Sq. @ 18" IF	6 In.^{2}
11	Albuquerque	Conchas (1938) New Mex.	22'		Horseshoe	8CB24		2'	2'-0"		Spacer Bars	1.25" Sq@6 1" Sq. @ 11"	
12	Kansas City	Wilson (1963) Kansas	12'	Flood Control	Circular			136'	2'-0"	4000		#4 @ 18 to #10 @ 12	
13	Baltimore	Whitney Point (1938) New York	13'		Horseshoe	6I 12.5	2'-8" to 4'	86'	1'-8"		#4 @ 24" #4 @ 12"	#7 @ 7-1/2	
14	Kansas City	Kanapolis (1940) Kansas	14'		Circular	7I 12	5'	118'	1'-6"		1" Sq. @ 18" 1" Sq. @ 36"	1-1/4"Sq@24 1-1/4"Sq@9	4.65 In^{2}
15	Huntington	Fishtrap (1964) Kentucky	15'-6"	Diversion & Flood Control	Horseshoe			143'	2'-0"				
16	Pittsburgh	Youghiogheny (1940) Penn.	19'		Circular	8I 25.5	3'	177'	1'-6"				
17	Pittsburgh	Tionesta (1937) Penn.	19'		Circular Inside Horseshoe Out	I-Beam Ribs	As Required	116'			#6 @ 18"	#8 @ 12"	1.57 In^{2}
18	Pittsburgh	Tionesta (1937) Penn.	19'	Non-pressurized	Circular Inside Horseshoe Out	I-Beams	As Required	116'	1'-9"		#6 @ 18"	#8 @ 12"	1.57 In.^{2}

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OP STEEL	AREA OF STEEL/FT.	STEEL LINER THICK.	SPACING OF BLOCKING POINTS	TUNNEL LENGTH	EST. COST PER LINEAR FOOT	GEOLOGICAL CONDITIONS ENCOUNTERED
@ 12 OF 1 @ 18 IF		None		2050'	$340.00	Pierre Formation, U. Cret., Clay-shale, montmorillonitic, soft to firm (average compressive strength 400 psi). Highly faulted and slickensided. Closely spaced bentonite seams from fraction of inch to several inches in thickness. Numerous joints whose orientation, spacing and extend varies between bentonite beds. Difficulties in tunneling occurred where concentration and intersections of rock defects were encountered, i.e., joints, faults, slickensides and bentonite seams. Degree of success of the 4 different tunneling machines used,was largely dependent on how close to heading ringbeams could be erected. This distance varied from 3.0 ft. to 11.5 ft; consequently when shale fallouts occurred the machine with its ringbeam erection jig located closest to heading, experienced much less difficulty in passing through reaches of heavy ground. No water problems. The shale slaked rapidly due to loss of moisture which required adding water to air for humidity control or protective coating like shotcrete.
@ 12 OF @ 9 IF		None		254'	Lump Sum Bid	
1 @ 12 1 @ 10		None		17335'	$640.00	
1 @ 18		None	Wood struts on 4' spacing where needed.	9420'	$715.00	
1 @ 9 OF 1 @ 9 IF		None		7560'	$1020.00	
1 @ 12 OF 8 @ 12 IF		11/16"	3'	15092'	$1460	
@ 12		None		641'	$ 425.00	Lee, Wise and Gladesville Formations, Penn. Shale hard, dense, sandy. Conventional drill and blast. Steel ribs w/blocking and/or rock bolts as required. No significant water.
ne		None		1252'	$ 320.00	Pocono Fm., Miss. Horizontally bedded sandy, silty shale and sandstone. Tunneling without difficulty, no ground water or roof falls encountered. Powder factors were 1.5 to 3.0 dynamite per c.y.
ne	None	None	None	1252'	$ 320.00	
" Sq. @ 18" IF	6 In.^{2}			320'		Dockum Group, Triassic. Red shale with thin clay partings that become plastic when wet. Pink shaly-sandstone, firm, compact and impervious, highly jointed with spacing of 1' to 25'. Sandstone average compressive strength 4,044 psi, range of compressive strength of all sandstone 1,067 psi to 9,717 psi. Shale - 411 psi to 2319 psi. No faults encountered. Drill and blast.
25" Sq@6 " Sq. @ 11"				310'		
@ 18 to @ 12		None		998'	$ 785.00	Dakota Formation, U. Cret. Shale, soft, massive, occasionally laminated by lenses of soft siltstone and sandstone. Support by CWF 15.5 ring beams spaced from 3' to 4' o.c. No water problem. Drill and blast.
@ 7-1/2				1349'		Hamilton Group, M. Dev. Shale, silty to sandy with interbedded sandstone. Shale thin to med. bedded w/valley-wall joints, nominal weathering. Sandstone is blocky. Support ribs for entire length, spaced 2'-8" at portals & 4' spacing throughout rest of tunnel. Liner plates & wood lagging at portals. No water. Drill and blast.
1/4"Sq@24 1/4"Sq@9	4.65 In^2			2350'		Ninnescah Formation, Permian. Shale, soft to firm, silty and occasionally calcareous. Bedding varies from thinly laminated to massive. Numerous fractures. No water problem. Drill and blast.
		None		720'	$ 680.00	Norton and Gladesville Formation, Penn. Shale, hard, dense. Conventional drill and blast. Steel ribs w/lumber lagging and/or rock bolts as required. No significant water inflow.
		None		1677'		Allegheny Fm., Penn. Horizontally bedded silt shale, coal, limestone, shaly sandstone and indurated clay. No unusual groundwater problems or roof falls. Drill and blast, powder factor 0.5 lbs. dynamite per c.y.
@ 12"	1.57 In^2	None		1875'		Pocono Fm., Miss. Horizontally bedded, medium hard silt shale with interbedded layers of sandy shale. Small thrust fault encountered with brecciated zone of 6" to 18" extending for a reach of 300' along tunnel from floor to roof and rising in a northeasterly direction perpendicular to the tunnel. Normal groundwater. Drill and blast with powder factor of 2.6 lbs. dynamite per c.y.
@ 12"	1.57 In.^{2}	None	None	1875'		

LINE NO.	CONSTRUCTED BY C. OF E. DISTRICT	PROJECT & APPROX. DATE DESIGN AND CONSTRUCTION	FINISHED DIAMETER	TUNNEL TYPE	TUNNEL SECTION	TEMP. SUPPORTS	SUPPORT SPACING	MAX. DESIGN HEAD	CONC. LINING THICK.	fc' P.S.I.	LONG. STEEL	HOOP STEEL	AREA OF STEEL/FT.	STEE LINE THIC
19	Prairie Farm Rehab-ilitation Agency	Gardiner (1969) Canada	20' 8"	Power	Circular	8WF40	3'		2'-6"			#18 @ 10"		
20	Garrison (Omaha)	Garrison (1949) No. Dakota	22'	Flood Control	Circular	10WF49	4'	0	2'-6'	3000	1.25" Sq. @ 16" EF	1" Sq. @ 24"	8.2 In.^{2} w/Ring Beam	Non
21	Garrison (Omaha)	Garrison (1949) No. Dakota	26'	Flood Control	Circular	10WF54	4'	200'	3'-0'		1.25" Sq. @ 16" EF	1-1/8" Sq. @ 24" EF		Non
22	Garrison (Omaha)	Garrison (1949) No. Dakota	29'	Power	Circular	10WF72	4'	200'	3'-0"		1.25' Sq. @ 16" EF	1.25" Sq. @ 24"	12.153 In.^{2}	Non
23	Omaha	Ft. Peck (1960) Montana	22'-4"	Power #2	Circular	10WF29	3.5'	261'	3'-9"			1.25' Sq. @ 9"		1' t 1-1
24	Ft. Peck	Ft. Peck (1933) Montana	24'-8'	Flood Control #3 & #4	Circular	7I 12.0 8WF21.0 10WF29	3'-6" to 5'	220'	3'-9"		53-1" Sq. IF	1"Sq. @20'OF 1.25"Sq. @9 IF		Non
25	Ft. Peck	Ft. Peck (1933) Montana	28'-3"	Power #1**	Circular	7I 12.0 8WF21 10WF29	3'-6" to 5'	1'-9"	1'-9"					Non
26	Sacramento	New Melones (1973) California	23'	Power & Diversion	Horseshoe	Shotcrete Rockbolts 8WF40	2'-6" 6'x6' 5'	595'	2'-6"	4000	#6 @ 24	#18 @ 12" IF #18 @ 12" OF		1-1
27	Nashville	Laurel Dam (1970) Kentucky	17' Upst. 19' Dnst.	Diversion & Power	Circular	8WF58 Rings	3' @ portals to 30' in.	Internal 363 External 260	1' in Diversion Sec.; 2'-9" in Power Portion	3000	#8 @ 18" #8 @ 21"	#18S @ 18" #14S @ 18"		11/1 to 13/1
28	Seattle	Flathead (1969) (Libby) Montana	24'-9" h. by 18' w.	Railroad	Horseshoe	6" WF20 and 8" WF34 Rockbolts →	Sets 2' to 5' 4' - 5' 4' - 6'		1'-6" Min. to a line	3500	#5 @ 24' Locally increased thru fault zone	#6 @ 12"		Non
29	Norfolk	Gathright (1972) Virginia	17'-6"	Outlet Diversion	Circular	8WF31 12' Rockbolts	Varied 5'x6'	249'	1'-6"	3000	#6 @ 18"	#9 @ 12"		3/4 1-1
30	Alaska	Snettisham (1968) Alaska	12'	Diversion	Horseshoe	Rockbolts		135'	None					Non
31	Alaska	Snettisham (1972) Alaska	13'-6" Unlined Portions 11'-6" Lined Portions	Power	Horseshoe	Rockbolts		76' Internal 1100' External	1'-0"	3000	#6 @ 12"	#11 @ 4-1/2"		Non
32	Alaska	Snettisham (1972) Alaska	8'-6"	Penstock	Circular	Rockbolts		900' Internal 300' External	1'-0"	3000	None	None		1/2' 1-1
33	Alaska	Snettisham (1972) Alaska	(L) 175' x (W) 32' (H) 425'	Powerhouse Chamber	Horseshoe	Rockbolts	5'x5'		None		None	None		Non
34	Colorado Division Highways	Straight Crk. (Eisenhower Memorial) 1968-1972 Colorado	(W) 34' x (H) 43'	Highway	Horseshoe	14WF287 (max.)	1' to 5'		Partial 3' to 5'	3000		None		Non
35	Phila-delphia	General Edgar Jadwin Dam (1958) Penn.	8'	Flood Control	Circular	None	None	79'	1'-6"	Not avail-able	None	#5 @ 12 for 100'		Non
36	Hunting-ton	John W. Flannagan (1960-61) Virginia	16'	Diversion & Flood Control	Horseshoe	Not Shown		216'	1'-10" Walls 2' - 2" Base	3500	Not shown	#6 - #8 @ 12"		Non

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P STEEL	AREA OF STEEL/FT.	STEEL LINER THICK.	SPACING OF BLOCKING POINTS	TUNNEL LENGTH	EST COST PER LINEAR FOOT	GEOLOGICAL CONDITIONS ENCOUNTERED
@ 10"				20000'		Bearpaw Fm., U. Cret. Clayshale, bentonite, faulted and reticulated with a complex system of joints and slickensides. Clay fraction of the shales contains 80% to 85% montmorillonite, the remainder being illite. Soft, medium and hard shales depending on degree of weathering. Shale swells after taking on moisture. Tunneled by use of the M-K tunneling machine. Tunneling encountered almost continuous face and arch falls in long reaches of first tunnel. The remaining 4 tunnels were tunneled w/o shut-downs except where an intensely slickensided & jointed zone was encountered, a few hundred feet from control shafts.
Sq. @ 24	8.2 In.^{2} w/Ring Beam	None		2400'	$1590.00	Ft. Union Formation, Tertiary (Paleocene). Massive pre-consolidated clayshale with zones of silt, fine sand and lignite beds up to 6' thick. Faults and joints insignificant. Lignite beds closely jointed, blocky and water bearing. Large test tunnel constructed and instrumented prior to awarding contract for the 8 tunnels, resulting in large savings to Government. Drill and blast full face w/ specially designed jumbo mounted on rails fastened to ring beams just below springline. Jumbo equipped with breast jacks to hold face and crown jacks to hold upper half of ringbeam segment. Mucker modified to allow continuous loading.
8" Sq @ ' EF		None		1200'		
25" Sq. @ 24"	12.153 In.^{2}	None		6000'		
25' Sq. @ "		1' to 1-1/16"	7'-6"	3756'	$ 720.00 Steel Liner only*	Bearpaw Formation, U. Cret. Clayshale, highly faulted, closely jointed and slickensided. Numerous bentonite seams from a fraction of an inch to 1' thick. Centrally located pilot tunnels for each bore (14 ft. x 16 ft.). Tunnels were enlarged by a top heading to full dimension from springline of pilot tunnel to crown. The bench was then removed to complete the full bore. No significant water. Because of blocky nature of shale, numerous blocks fell from crown.
Sq. @20'OF 25"Sq. @9 IF		None		13883'		
		None		5379'		
@ 12" IF @ 12" OF		1-1/8"	5'	3790'		Sierra foothills metavolcanics. Downstream portion of tunnel in excellent greenstone and good quality slate which is steeply foliated normal to the tunnel axis. Upstream quarter of tunnel is greenstone which has been variably effected by serpentine and talc which lowers the overall strength quality. Two faults encountered, one of which is a contact fault between the rock types. Faults no particular problem. Jointing blocky resulting in ground w/some slicks on jt. surfaces. No significant water. Excavated by top heading and bench, drill and blast.
S @ 18" S @ 18"		11/16" to 13/16"	4' on C	1315'	$1327.00	Rockcastle Member of Lee Formation, Penn. Flat lying sandstones, massive, fine grained sandstones w/conglomerate zones. Compressive strength 6,000 to 13,000 psi. Minor jointing. No water problems. Twelve-foot pilot bores were driven short distances from each portal before advancing full face. Recessed rockbolts used in pilot bores. Major excavation problem was contractors inability to keep perimeter blast holes aligned.
@ 12" ed e		None	4' Maximum	36955'	$1228.00	Ravalli Grp. & Prichard Fm. of Precambrian Belt Series. Argillite, quartzite & meta-sandstone w/minor limestone & calcareous argillite. Range from moderately hard to very hard & are thin to medium bedded Average compressive strength 20,000 psi. Well developed jt. system. Folded & faulted. Excavation full face. Each heading made about 80 gpm, most of which drips & seeps from joints and rock bolt holes.
@ 12"		3/4' - 1-1/2"		1181'	$1555.00	
		None		800'		Clifton Forge S. S. and Lower Keyser Ls. Fm. of Silurian age & Tonoloway Ls. Fm. of Devonian Age. Driven thru flank of anticline. Clifton Forge & Lower Keyser Fms. presented few problems but Tonoloway is a thin bedded, argillaceous & sandy Ls. w/some joints. Highly weathered & solutionized along jts. forming cavernous areas. Largest cavern crossed tunnel from springline to springline, was 3' wide at invert extended at least 20' beyond tunnel wall and was clay filled. Clay was excavated beyond payline, backfilled w/concrete & pressure grouted behind the concrete. Two major & 2 minor jts. sets encountered, w/no major problems. No significant water. Excavated full face by drill & blast. U.s. portal-transition area supported by tunnel sets installed on concrete sills poured in adits driven at each springline.
@ 4-1/2"		None		8432'	$ 518.00	
ne		1/2" - 1-1/16"	6'-8"	1200'	$1653.00	No fm. given. Cretaceous (?). Quartz diorite and granite gneiss associated w/the Coast Range batholith. Three minor faults were crossed in the power tunnel w/no particular problem. Relatively thin (up to 10'), vertical basalt dikes w/closely spaced jts. were encountered & required installation of tunnel lining. No significant water encountered. Tunnels excavated full face, powerhouse excavated by top heading and bench. Rock of excellent quality.
ne		None			$ 200.00/yd.	
ne		None	Variable	8972' (1.7 Miles)	$13000.00	Located near the eastern flank of the Rocky Mtns. at 11,050' elev., highest ventilated tunnel in the world. Bedrock was 75% granite & 25% metasedimentary gneiss & schist that occurred as migmatite inclusions w/numerous shear zones, faults & joints. Over 3,600' of tunnel was thru squeezing ground & over 1800' required excavation thru the use of concrete filled multiple drifts around the periphery to support the bad rock, while center of tunnel was excavated. Most of remainder of tunnel was excavated by top heading & bench method. Little water encountered except near portals during spring thaw.
@ 12 r 0'		None	None	553.4'	$ 310.00	Catskill Fm. (Red beds). Penn. Dev., siltstone, sandstone and shale. 10-15,000 psi comp. strength flat lying beds, wide jt. spacing, no water problem. Drill-blast, rockbolted.
- #8 @ 12"		None	None	780'	$ 620.00	Norton Fm., Penn. Sandstone upper two thirds of tunnel section, siltshale lower one-third of tunnel cross-section. Sandstone massive hard, cemented. Siltshale, hard, cemented. Both materials easily excavated by drilling and blasting. Rock self-supporting except for occasional safety rockbolts. No water.

LINE NO.	CONSTRUCTED BY C. OF E. DISTRICT	PROJECT & APPROX. DATE DESIGN AND CONSTRUCTION	FINISHED DIAMETER	TUNNEL TYPE	TUNNEL SECTION	TEMP. SUPPORTS	SUPPORT SPACING	MAX. DESIGN HEAD	CONC. LINING THICK.	fc' P.S.I.	LONG. STEEL	HOOP STEEL	AREA OF STEEL/FT.	STEEL LINER THICK.	BL
37	Vicksburg	Blakeley Mountain (1948-50) Arkansas	19'	Diversion	Circular	6H20 @ 3' to 8WF24 @ 2'		21'	2'-0"	3000	#6 @ 12 EF	1" Sq. @ 121F 1" Sq. @ 120F		None	
38	Vicksburg	Blakely Mountain (1948-50) Arkansas	19'	Flood Control	Circular	6H20 @ 3' to 8WF24 @ 2'		211'	2'-0"	3000	#6 @ 12 EF	1" Sq. @ 12F		None	
39	Vicksburg	Blakely Mountain (1948-50) Arkansas	30'	Power	Circular	8H34.3 @ 2' to 10WF33 @ 3'	2' to 3'	211'	2'-6"	3000	#6 @ 24" EF	#6 1-1/4" Sq. @ 12"		None	
40	Vicksburg	Blakely Mountain (1948-50) Arkansas	30'	Diversion	Circular	8H34.3 to 10WF33	2' to 3'	211'	2'-6"	3000	#6 @ 24" EF	#6 1-1/4" Sq. @ 12		None	
41	Tulsa	Tenkiller Ferry (1948) Oklahoma	19'	Outlet	Circular	8 I 25.5	3'-0"	142'	1'-6"	3000	#5 @ 24"	#6 @ 12"		None	
42	Tulsa	Tenkiller Ferry (1949-50) Oklahoma	19'	Outlet	Circular	8 I 25.5	3'	185'	1'-6"	3000	#5 @ 24"	#6 @ 12"		None	
43	Tulsa	Tenkiller Ferry (1949-50) Oklahoma	19'	Penstock	Circular	8 I 25.5	3'	185'	1'-6"	3000	None	None		1/2"	
44	Hunting-ton	Mohawk (1935) Ohio	20'	Non-Pressurized	Horseshoe	None shown		90'	2'-0"		#8 @ 36	1.25 In. Sq. bars @ 12"	3.125 In.^{2}	None	
45	Hunting-ton	Sutton Lake (1956-58) W. Virginia	20'-6"	Railroad	Horseshoe	Not shown		0	1'-8"	3500	None	None	None	None	
46	Pittsburgh	Conemaugh Dam (1946) Penn.	28' x 30'	Railroad	Horseshoe	Not shown		(1600 PSF)	2'-8"	4400	#6 @ 24"	#6 @ 12"		None	
47	Vicksburg	DeGray (1964) Arkansas	29'	Power	Circular	8WF31 Horseshoe	3'	365'	2'-6"	3000	#9 @ 121F #6 @ 120F	#14 @ 121F #18 @ 120F		7/8" to 1-1/8"*	
48	Hunting-ton	Summersville (1960-62) W. Virginia	29'	Diversion & Flood Control	Circular	Not shown		311.6'	2'-5"	3500	Not shown	#8 - #11 @ 12		1"	
49	USBR	Carter Lake USBR (1950) Colorado	8'	Pressure	Circular	Horseshoe ring beams	Varies	140'	5 1/2"		24 - #5 evenly spaced	#8 @ 6" to 1-1/4" Sq. @	4 In.^{2}	None	
50	USBR	Keyhole Dam USBR (1951) Wyoming	8'-3" x 9'-6"	Diversion	Horseshoe	1" dia. 6' rock-bolts 4' o.c.			1'-3"						
51	Tulsa	Gillham (Under Construction) Arkansas	10'	Outlet	Circular	Not shown		142'	1'-6"	3000	Not shown	#8 @ 12 #6 @ 12		None	
52	Phila-delphia	Alvin R. Bush (1962) Penn.	13'	Flood Control Outlet	Horseshoe	4WF13	4'	152.7'	1'-6"	3000	Not shown	#6 @ 18"		None	
53	Hunting-ton	Grayson (1964-65) Kentucky	14'	Diversion & Flood Control	Circular	Not shown		83'	2'-0"			#6 & #8 @ 12		None	

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STEEL	AREA OF STEEL/FT.	STEEL LINER THICK.	SPACING OF BLOCKING POINTS	TUNNEL LENGTH	EST. COST PER LINEAR FOOT	GEOLOGICAL CONDITIONS ENCOUNTERED
. @ 121F . @ 120F		None	None	747'	$ 530.00	Shale with intermittent sandstone strata, that are highly contorted and folded being part of an overturned anticline. The downstream portion of the tunnels were driven perpendicular to the strike and about 30° into the dip. In the upstream portions the tunnels were driven parallel to the strike and at a bedding dip of less than 10°. Badly weathered shale was encountered for approximately 200 ft. in the downstream portion of the tunnels. Drill and blast. No significant water problems. Portal failure on one tunnel.
. @ 12F		None	None	980'	$ 530.00	
/4" Sq.		None	None	883'	$1320.00	
4" Sq. 2		None	None	622'	$1320.00	
		None	None	557'	$ 890.00	Atoka Fm., Penn. Interbedded sandstones and shales. Excavation encountered hard, fresh rock, several minor faults and open joints.
2"		None	None	557'	$ 890.00	Pennsylvanian sequence (?). Shale, sandstone. Logs show both weathered and unweathered shale and sandstone. No mention of adverse rock conditions encountered in tunnel. Steel sets. Drill and blast. No water problems.
		1/2"	None	579'	$ [illegible] 00	[illegible]r and Lower Mahoning Formation, Penn. Sandstone and shale. Medium hard, well cemented sandstone and hard, moderately resistant shale. Conventional drill and blast. Timber support w/timber lagging. No water.
n. Sq. @ 12"	3.125 In.^{2}	None	None	330'		Conemaugh Fm., Penn. Horizontally bedded sandstone & shales. Numerous roof falls were experienced due to weak bedding planes which allowed large blocks of jointed sandstone to loosen over the working area at numerous locations. Powder factors were 4 1/3 lbs. dynamite per c.y. for 17' high x 14' wide [illegible] tunnel & 1 lb./yd^3 for main tunnel, 35'-4" wide x 32'-3" high. No serious groundwater problem.
	None	None	None	555'	$ 915.00	Jackfork Fm., Miss. Sandstone & interbedded shale w/slickensided surfaces at interface between the two rock types. The sandstone is hard, fine to med. grained & quartzitic. The shale is black, hard, thinly bedded and fissile. Beds dip [illegible]°. Three principal jt. sets perpendicular to the bedding with the most prominent set paralleling the strike of the beds. Several faults encountered. Few minor water seeps. Drill and blast. Construction problems occurred at upstream portal due to improper installation of steel sets.
2"		None	None	2660'	$ 610.00	Nuttall Fm., Penn. Sandstone & shale w/occasional coal horizons. Very hard, shaly sandstone & sandy shale. No significant water. Conventional drill & blast. Temporary support - steel ribs w/ steel lagging. Tunnel length 2,000 ft. circular 29 [illegible], concrete lined w/downstream valved control. Steel liner downstream of dam axis.
121F 120F		7/8" to 1-1/8"*	3'-0"	1667'	$1490.00	Excavation of the mile long tunnel was through Fountain, Ingleside, Satanka, Lyons and Lykins formations, of Penn. and Permian age. The Fountain formation was soft sandstone and shale which slacked slightly when exposed to air. With the exception of [illegible] feet in the Satanka formation, the entire Ingleside and Satanka formations were unsupported. Heavy ground was encountered at the contact between the Lyons and Lykins formations. This contact consisted of very soft mud which required hand augering for blast holes. The support steel in the Lykins shale formation was supplemented by a total of 116 roof bolts. The bolts were used, two on each side of one course of steel, to pin the steel sets in place and prevent settling due to lack of support by foot blocks in the mud. A total of 858, 6-inch H-beam steel sets were installed at 4 foot and 6 foot centers. Maximum water flow encountered was 150 gpm at 30 psi pressure. It was grouted off with 242 sacks of cement. Small seeps were encountered throughout most of the tunnel.
11 @ 12		1"	3'-0"	1862.4'	$1530.00	
" to 1- q. @	4 In.^{2}	None		5890'		
				654'		Lakota Fm., Cretaceous. Sandstone, massive to thinly bedded, med. hard to very soft. Vert. jointing throughout tunnel. A few vertical clay seams from fractions of an inch to several inches in thickness. The larger clay-filled seams occurred near the outlet end of the tunnel, generally increasing in width according to proximity with the portal.
12 12		None		627'	$ 765.00	Stanley Shale Fm., Miss.-Penn. Quartzitic sandstones and interbedded shales. Excavation encountered minor fault (healed) which gave no problem and numerous joints and fractures open to filled with secondary minerals.
8"		None		768'	$ 460.00	Catskill Fm., (Redbeds), Penn. Dev., Siltstone, sandstone, shale comp. strg. 10-15,000 psi, mod. jointing, [illegible] water, rock failure at one portal, excavate by drill-blast, steel sets.
8 @ 12		None		390'	$ 930.00	Lee Formation of the Pottsville series, Penn. Sandstone, moderately hard, medium grained, brown, sugary, cross-bedded with soft weathered zones. Conventional drilling and blasting. Steel ribs w/lumber lagging and [illegible] rock bolts as required. No significant water inflow.

LINE NO.	CONSTRUCTED BY C. OF E. DISTRICT	PROJECT & APPROX. DATE DESIGN AND CONSTRUCTION	FINISHED DIAMETER	TUNNEL TYPE	TUNNEL SECTION	TEMP. SUPPORTS	SUPPORT SPACING	MAX. DESIGN HEAD	CONC. LINING THICK.	fc' P.S.I.	LONG. STEEL	HOOP STEEL	AREA OF STEEL/FT.	STEEL LINER THICK.
54	Huntington	Pleasant Hill (1935) Ohio	14'-3"	Non-pressure	Circular Inside Horseshoe Out	6 I 12.5	Not shown	94'	1'-6"		#8 @ 36"	1.25 Sq. @ 12	4.688 In.^{2}	None
55	Huntington	Pleasant Hill (1935) Ohio	19'	Spillway	Horseshoe	6 I 12.5	Not shown	94'	2'-0"		#8 @ 36"	1.25 Sq. @ 12	4.688 In.^{2}	None
56	USBR	Glen Canyon USBR (1961) Arizona	41'	Spillway	Circular	Occasional Rockbolts and Mine Ties			0.8" ft. of dia.		Used Newmark's method for stresses in elastic foundation to get liner stresses where required.			
57	USBR	Glen Canyon USBR (1961) Arizona	41'	Diversion	Circular	Occasional Rockbolts and Mine Ties			1'-3" u.s. 2'-9" d.s.		Same as above			-
58	USBR	Glen Canyon USBR (1961) Arizona	41'	Diversion	Circular	Occasional Rockbolts and Mine Ties			1'-3" 2'-9"					
59	Albuquerque	Abiquiu Dam Rio Chama (1956) New Mexico	12'-0"	Flood Control	Circular	Not shown	Not shown	301.9'	1'-6"	3000	Not shown	#7 @ 18" to #11 @ 12"		None
60	USBR	Eklutna Proj. USBR (1965) Alaska	9'-0"	Pressurized	Circular	H-Beams, #8 rock bolts	Not shown	74'	5 1/2"		30 - #5 bars	1" Sq. @ 6' #8 @ 9"		None
61	Tulsa	Broken Bow (1962 - 64) Oklahoma	17'	Diversion	Circular	Not shown		100'	1'-0"	3000	Not shown	#6 @ 12"		None
62	Tulsa	Broken Bow (1962 - 64) Oklahoma	25'	Penstock	Circular	Not shown		253'	2'-6"	3000	None required	None required		5/8" to 1-1/4"
63	Omaha	Fort Randall (1956) S. Dak.	22'	Outlet Works	Circular	8WF24	4'	155'	2'-0"	2500	1 In. Sq. @ 12"	1 In. Sq. @ 16"		None
64	Omaha	Fort Randall (1956) S. Dak.	22'	Power	Circular	8WF24	4'	155'	2'-0"	2500	1 In. Sq. @ 12"	1-1/4" Sq. @ 12"		None
65	Omaha	Fort Randall (1956) S. Dak.	28'	Outlet Works	Circular	10WF33	4'	165'	2'-3"	2500	1 In. Sq. @ 12"	1 In. Sq. @ 16"		None
66	Omaha	Fort Randall (1956) S. Dak.	28'	Power	Circular	10WF33	4'	165'	2'-3"	2500	1 In. Sq. @ 12"	1-1/4" Sq. @ 12"		None
67	Ft. Worth	City of Fort Hood (19) Texas	5'-9"	Water Supply	Horseshoe	Not shown		123'	1'-3"	3000	Not shown	#6 & #7 @ 12"		None
68	International Boundary and Water Commission	Amistad Dam* (1970) Texas	14'-6"	Power & Flood Control	Circular	Not shown		268'	1'-6"	4000	None	None		1/2" to 13/16"
69	Louisville	Cagles Mill Res., Mill Creek (1948-49) Indiana	12'-0"	Diversion Flood Control	Horseshoe	Not shown		109'	1'-6"		None	None		None

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OOP STEEL	AREA OF STEEL/FT.	STEEL LINER THICK.	SPACING OF BLOCKING POINTS	TUNNEL LENGTH	EST. COST PER LINEAR FOOT	GEOLOGICAL CONDITIONS ENCOUNTERED
1.25 Sq. @ 12	4.688 In.^{2}	None		78'		Waverly series (Fm?), Miss. Clayshale, medium hard, sandy. Conventional drilling and blasting. Temporary support with "I" beams and steel liner plates. No water.
1.25 Sq. @ 12	4.688 In.^{2}	None		612'		
method for c foundation to where re-						Navajo Formation, Jurassic. Navajo sandstone is over 1400 ft. thick at the damsite. It extends from approximately 1,000 feet above river level to more than 400 feet below river level. It is massive with pronounced crossbedding and is remarkably uniform over wide areas. Rough bore 43.5 ft. to 46.5 ft. driven by drilling and blasting. Rate of advance about 340 feet per month. Some difficulties were experienced because of the roof of the tunnel slabbing off along the left side, possibly due to tunnel wall running nearly parallel to the strike of steeply dipping crossbeds. This slabbing required the use of many additional roof bolts and mine ties of steel-ribbed 2" by 6" by 13 foot channels.
			None	2749'		
				3011'		
#7 @ 18"to #11 @ 12"		None		2078'	$ 720.00	Abo Fm., Upper Permian. Mudstone, silty, blocky to massive, no open joints. Unconfined compressive strength 1,900 psi. Dry density 147 lbs/ft. Drill and blast. No significant water.
1" Sq. @ 6' #8 @ 9"		None		23723'		Formation name not given. Graywacke and argillite, complexly folded and faulted with numerous water bearing channels. Many of the fracture and bedding planes contained graphite and slickensides. A major cave-in and loss of heading, occurring with a flow of water estimated at 18,000 gpm, caused suspension of work at the heading for 2 months. Tunnel design was changed to allow "under the track drainage" in a steel flume section. The flow eventually stabilized at 1,300 gpm. Steel supports consisted of 4", 5" and 6' H-beams, w/most of them being 5" H-beams at 4' spacing. Roof bolts were used for support in several sections of tunnel but proved to be ineffective and their use was abandoned.
6 @ 12"		None		1090'	$ 830.00	Stanley Shale Fm., Penn.-Miss. Argillites and minor sandstones, limestone and tuff seams of Stanley shale. Interbedded shale and novaculite, silicious limestones, beds of tuffs and some sandstone beds of the Arkansas Novaculite Formation - Miss. - Dev. age. Excavation encountered several faults (which necessitated additional supports), fractures and joints.
None required		5/8" to 1-1/4"	3' to 4'	1800'	$1875.00	
1 In. Sq. @ 16'		None		2834'		Niobrara Formation, U. Cret. Chalk and shaly chalk. Dry densities vary from 80 to 115 lbs. per cu. ft., compressive strengths range from 700 psi to 1400 psi. Natural moisture from 16% to 32%. Tunnels were driven through lower Ft. Hayes member of the formation which has the higher compressive strengths lower moisture and contains fewer bentonite seams than does the upper Smoky Hill member. The thickest bentonite seam in the tunnel horizon averaged 0.15 of a ft. The chalk is massive, except for widely spaced joints and faults healed with calcite. The tunnel peripheries were cut by use of a shale saw mounted on a ring gear attached to the front end of a jumbo. The center core was then drilled and blasted. Occasional faults behind the face caused the center core to slide out before it was blasted. No significant water inflows.
1-1/4" Sq. @ 12'		None		1720'		
1 In. Sq. @ 16"		None		658'		
1-1/4" Sq. @ 12"		None		5264'		
#6 & #7 @ 12"		None		330'	N.A.	Comanche Peak Fm., L. Cret. Limestone, moderately hard, shaly, nodular, containing numerous thin calcareous shale beds. Conventional drilling and blasting. No support required. No water.
None		1/2" to 13/16"	2'-6'	1620'	$ 800.00 est.	Georgetown Fm., Cretaceous. Limestone, moderately hard, fine grained, slightly argillaceous. Contains numerous thin persistent shale seams, abundant styolitic structures with occasional faults having maximum displacement less than 12 feet. All tunnel excavations in dry rock. No rock support required except a few rock bolts above tunnel portals with some timber support at portal tunnel 4.
None		None		398'	$ 525.00	St. Genevieve Formation. Miss., limestone - hard, med. grained crystalline. Generally thick bedded some shale seams at upstream portal. Very little solutioning on joints. Compressive strength 10-14,000 psi. No faults - joints spacing average of 6 - 12 feet cut approximately 45^0 to tunnel alignment. Excavation by drill and blast with minor overbreak. No water problems.

LINE NO.	CONSTRUCTED BY C. OF E. DISTRICT	PROJECT & APPROX. DATE DESIGN AND CONSTRUCTION	FINISHED DIAMETER	TUNNEL TYPE	TUNNEL SECTION	TEMP. SUPPORTS	SUPPORT SPACING	MAX. DESIGN HEAD	CONC. LINING THICK.	fc' P.S.I.	LONG. STEEL	HOOP STEEL	AREA OF STEEL/FT.
70	Kansas City	Pomme de Terre (1959) Missouri	12'-0"	Flood Control	Circular	Not shown		143'	1'-0"	4000	Not shown	#6 @ 12"	
71	Portland	Hills Creek (1962) Oregon	12'-0"	Penstock	Circular	Not shown		200'	1'-6" Min.	3000	None required	None required	
72	Portland	Hills Creek (1962) Oregon	13'-9"	R. O.	Circular	Not shown		Nominal	1'-6" Min.	3000	#7 @ 12"	#9 @ 12"	
73	Portland	Hills Creek (1962) Oregon	23'-0"	Diversion	Horseshoe			Nominal	1'-2" Min.	3000	None required	None required	
74	Portland	Green Peter (1972) Oregon	29'-0"	Diversion	Horseshoe	Not shown		Nominal					
75	Portland	Green Peter (1972) Oregon	29'-0"	Diversion	Horseshoe	Not shown		Nominal	1'-6"	3000	None	None	
76	New England Division	Colebrook River Farmington R. (U. C.) Conn.-Mass.	10'-0"	Flood Control	Circular	Not shown		210'	1'-3"	4000	#6 @ 12"	#11 @ 8"	
77	Mobile	Buford (1958) Georgia	10'-0"	Power	Circular	Not shown		112'	2'	3000	None required	None required	
78	Mobile	Buford (1958) Georgia	13'-3"	Flood Control	Circular	Not shown		0	1'-6"	3000	#6 @ 12"	#8 @ 12"	
79	Mobile	Buford (1958) Georgia	22'-0"	Power	Circular	Not shown		112'	2'	3000	None required	None required	
80	Mobile	Buford (1958) Georgia	22'-0"	Power	Circular	Not shown		112'	2'	3000	None required	None required	
81	Los Angeles	Alamo Dam (U. C.) Arizona	12'-0"	Flood Control	Circular	Not shown		260'	1'-10"	3000	#5 @ 18"	#6 @ 12"	
82	Los Angeles	Alamo Dam (U. C.) Arizona	12'-0"	Flood Control	Circular	Not shown		55'	1'-10"	3000	None	None	
83	Walla Walla	Dworshak Dam (U. C.) Idaho	40'-0"	Diversion	Horseshoe	10WF49	5'-0"	Free Flow	1'-6"	4000	None	#9 @ 12IF 4x4 #9 OF	
84	New England Division	Littleville, Westfield River (1965) Mass.	8'-0"	Flood Control	Horseshoe	4WF13	4'-0"	83.5'	1'-3"	4790	#4 @ 16"	#4 @ 16"	
85	New England Division	North Springfield (1960) Vermont	12'-9"	Flood Control	Horseshoe	Not shown		36'	1'-7"	3660	#6 @ 12"	#8 @ 12"	
86	New England Division	Union Village Dam (1950) Vermont	13'-0"	Pressure	Horseshoe	None shown		144'	1'-0"		#6 @ 24"	#7 @ 12"	1.203 In.^{2}
87	New England Division	Ball Mt. West River (1961) Vermont	13'-6"	Flood Control	Circular	None shown		65'	1'-3"	3280	None	None	
88	New England Division	Worcester Diversion Blackstone (1957 - 60) Mass.	16'-0"	Flood Control	Circular	Not shown		0	1'-3"	3690	None	None	

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STEEL	HOOP STEEL	AREA OF STEEL/FT.	STEEL LINER THICK.	SPACING OF BLOCKING POINTS	TUNNEL LENGTH	EST. COST PER LINEAR FOOT	GEOLOGICAL CONDITIONS ENCOUNTERED
hown	#6 @ 12''		None		514'	$ 607.00	Jefferson City Formation Dolomite, hard, dense to finely xln. Thin to thick bedded, some fine fractures and healed faults. No water problems. Drill and blast. Support - none required.
uired	None required		3/4' 1''	5'-0''	667'	$1620.00	Tuff Breccia, massive, faulted. One prominent vertical fault zone about 10 feet wide paralleled the tunnel crown for much of its length. Rockbolts, mine ties, steel sets where required. No water. Drill and blast.
12''	#9 @ 12''		7/8''	5'-0''	545'	$1690.00	Massive Tuff Breccia, faulted. Six foot long rock bolts installed locally at fault intersections in the crown and portals. Steel sets where needed. No water. Drill - blast.
uired	None required		None	None	1150'	$ 505.00	Tuff Breccia with basalt interbeds. Fault planes and shear zones. Basalt sill rock bolted. Steel sets where required. Drill and blast.
					400'	$ 500.00	Tertiary basalt, porphyritic; lapilli tuffs and flow breccias. Rock contains both random and continuous systems of open intersecting joints, stained and slightly decomposed. Numerous shear zones and faults containing crushed rock, slickensides and plastic fines. No water problems. Drill and blast. Steel ribs for support.
	None		None	None	650'	$ 900.00	
12'	#11 @ 8'		3/8'' 20'	5'-0''	683'	$ 483.00	Pre-Cambrian (?) Gneiss, hard, coarse grained and fresh at upstream end of tunnel. Gneiss, schistose, hard, generally fine grained at downstream end of tunnel. Dip of foliation 60^0 to 75^0. Drill and blast. No water problem. Steel ribs and bents as required.
uired	None required		1/2'' to 1-1/16''	3'-0''	110'		
12''	#8 @ 12''		None		246'		Pre-Cambrian (?) Granite and granite gneiss, with some soft layers in weathered zone, but generally hard and massive in unweathered zones. Gneissic structure dips less than 25^0 with local distortions to 90^0. Drill and blast. No support required. No significant water.
uired	None required		1/2'' to 1 -1/16''	3'-0''	246'	$1084.00	
uired	None required		1/2'' to 1 -1/16''	3'-0''	246'	$1084.00	
18''	#6 @ 12'		None		458'	N. A.	Pre-Cambrian, undifferentiated metamorphics overlying a banded gneiss. Blocky jointed and seamy, particularly at downstream portal. A number of faults shown on drawings, but no information on problems encountered, if any. Drill and blast. Support rock bolts at portals, steel sets in tunnel. No significant water.
	None		None		504'	N. A.	
	#9 @ 12IF 4x4 #9 OF		None		1721'	$1375.00	Massive granite gneiss, Orofino series, Pre-cambrian (Belt Series). A metamorphsism of the Idaho batholith which lies to the east. Foliation is relic bedding dipping 35^0 (apparent) to tunnel line. At least three distinct joint systems, which included vertical joints and joints parallel to foliation, separated the rock into wedge shaped blocks and resulted in fallouts. Three faults encountered, one of which gave some problems. Tunnel excavated full face. No water problems.
16''	#4 @ 16'		None		285'	$ 370.00	Schist, containing quartz stringers, biotite and garnet. Coarse grained, moderately hard. Slight water flows. Support by steel sets where required. Foliation planes in schist dip from 45^0 to 70^0 causing rough overbreak in crown and one rib. Conventional drill and blast.
12''	#8 @ 12''		None		600'	$ 509.00	Cavendish Schist, U. Cambrian. Schist and gneiss, highly folded and faulted with steeply dipping foliation planes. Several shear zones required lagging, otherwise, rockbolts and steel sets used. Insignificant water flows. Drill and blast - lined drilled where required to prevent opening joints and foliation planes. No significant water.
24''	#7 @ 12'	1.203 In.^{2}	None		1178'		Gile Mt. Fm., Lower Devonian. Phyllite. Very conspicuous and well developed cleavage dip essentially vertical. Strike of foliation nearly normal to tunnel alignment. Drill and blast. No construction history available.
	None		None		865'	$ 487.00	Schist (sericitic, chloritic, garnetiferous) with numerous grantitized zones. Foliation dips 30^0 to 40^0 downstream. Several joint sets, some slickensided. Drill and blast. Insignificant water. Support, partial steel sets, few rockbolts.
	None		None		4300'	$ 500.00	Till, Pleistocene. Intake and first 500 feet of tunnel in glacial till ranging from clayey sand through gravelly clay to sandy silt. When dry, till remains firm and stands well on slopes; when wet sags and flows. Remaining 3800 ft. of tunnel in phyllite, schist, gneiss with variable dips of the foliations from 30^0 to 40^0. Rough bore about 20 ft. Support by ringbeams in earth section and horseshoe sets in rock. Some rock sections were self-supporting.

LINE NO.	CONSTRUCTED BY C. OF E. DISTRICT	PROJECT & APPROX. DATE DESIGN AND CONSTRUCTION	FINISHED DIAMETER	TUNNEL TYPE	TUNNEL SECTION	TEMP. SUPPORTS	SUPPORT SPACING	MAX. DESIGN HEAD	CONC. LINING THICK.	fc' P. S. I.	LONG. STEEL	HOOP STEEL	AREA OF STEEL/FT.	STEE LINE THIC
89	Sacramento	Terminus Dam (1962) California	12'-9"	Flood Control	Circular	Not shown		238'	1'-6"	3000	Not required	Not required		No
90	Mobile	Carter's Dam (1964) Georgia	23'	Diversion	"D" Shape	None shown		0	None					Non
91	Portland	Cougar (1964) Oregon	10'-6"	Penstock	Circular inside, Horseshoe, out	Not shown		270-650'	2'-9"	3000	None required	None required		5/8" 1
92	Portland	Cougar (1964) Oregon	20'-6"	Diversion	Horseshoe	Not shown		Nominal	None					Non
93	Portland	Cougar (1964) Oregon	17'-10"	R. O.	Circular	Not shown		Nominal	2'-2"	3000	#7 @ 12"	#9 @ 12"		Non
94	Portland	Foster (Uncompleted) Oregon	32'	Diversion	Horseshoe	Not shown		Nominal	None					Non
95	Sacramento	Black Butte Dam (1963) California	23'	Flood Control	Circular	Not shown		135'	2'-6"	4500	None required	None required		Non
96	Walla Walla	Lucky Peak (1956) Idaho	23'	Flood Control	Circular	Not shown		240'	1'-9"	3000	None	None		1/2" 3/4"
97	Seattle	Howard A. Hanson Dam (1962) Washington	19'-19"	Diversion & Flood Control	Horseshoe	Steel sets	4' to 6'	4'	2'-0"	5000	#5 @ 18"	#9 @ 7-12		Non
98	Portland	Blue River (Uncompleted) Oregon	23'-6"	Diversion	Circular	Not shown		Nominal						
99	Portland	Big Cliff (1953) Oregon	28'	Diversion	Horseshoe	Not shown		Nominal	None		None	None		Non
100	Los Angeles	Painted Rock Res. (1960) Arizona	25'	Flood Control	Circular	Not shown		0	2'-2"	3000	None	None		Non
101	Los Angeles	Isabella Dam (1953) California	14'-9"	Flood Control	Circular	Not shown		176'	2'-6"	3000	None	None		Non

2

HOOP STEEL	AREA OF STEEL/FT.	STEEL LINER THICK.	SPACING OF BLOCKING POINTS	TUNNEL LENGTH	EST. COST PER LINEAR FOOT	GEOLOGICAL CONDITIONS ENCOUNTERED
Not required		None		1060'	N. A.	Lemon Cove Fm., Triassic (?). Schist, quartzitic, micaeous, with numerous igneous dikes and marble pods. Moderately jointed with three faults which caused no problems. Sets used for 100 ft. to support rock in marble pod area. Excavated full face. No significant water problems.
		None		2405'	$ 195.00	Ocoee series, Pre-Cambrian and Lower Cambrian. Metamorphic rocks grading between conglomeratic quartzite, argillaceous quartzite and phyllite. The most dominant types are argillaceous quartzite and phyllite. The rock is highly contorted, folded and faulted. Drill and blast. Safety and pattern bolts, no chain link or shotcrete required. No significant water.
None required		5/8" to 1"	4.5' - 10.5'	1043'	$ 728.00	Tertiary Volcanic Rocks. Basalt, fine grained, xln, bedded tuffs, and hard brittle tuff. Gouge zones up to 3". One fault zone 25' wide, but no problems. No large water inflow. Support, 3/4" hi-strength rockbolts, 5' o.c. 6'-8" long, set radially in arch. Mesh and bolts in brittle tuff reach of tunnel. Drilling and blasting. Several joint sets.
		None	None	1843'	$ 163.00	
#9 @ 12'		None	None	993'	$ 376.00	Tertiary Volcanic Rocks. Hard, xln, columnar basalt and bedded tuffs intruded by basalt dikes. Columnar jointed basalt formed large loose blocks, requiring extensive scaling. No large water flows. Rockbolt support - split - wedge type 7/8" to 1" dia., 5' to 10' long, used where needed.
		None	None	565'	$ 500.00	Porphyritic basalt, sandy, ashy and lapilli tuffs and flow breccia. High angled faults, joints and shear zones, some open with clay filling. Excavation by heading and bench method. Drill and blast. No water problems reported.
None required		None		545'	$ 800.00	Three formations encountered: Tertiary basalt & basalt breccia in thin flows; Tertiary conglomerate & mudstone; Cret; Chico Fm., shale & some limestone. All formations dip from u/s to d/s. Lost d/s portal in basalt during construction & had to move in 100'. One large fault encountered w/numerous associated shears. Most of tunnel excavated in mudstone which required breast boards. Contractor tried full face excavation, got into trouble and went to heading and bench. Excavated by using everything from blasting to air spades. Some water seepage which created problems in trying to clean soft rock prior to concreting.
None		1/2" to 3/4"	4'-0"	1120'	$ 840.00	Miocene basalt, ranging from hard, massive and columnar jointed to closely jointed and fractured, faulted and chemically altered containing 1"-8" thick clay seams. Support varied from none to steel sets and lagging. Excavation method varied from full face to 3 pilot drifts depending on rock conditions. No water problems. Drill and blast.
#9 @ 7-12		None	None	880'	$1250.00	Fm. and age not given. An intercalated series of soft andesitic tuffs & harder crystalline andesite, basalts & felsites. Fractures moderately spaced to intense w/several fault zones dipping u/s and characterized by 2 to 12" of gouge. Excavation was full face.
				1797'	$ 274.00 w/o ribs or rock bolts	Fresh andesite thruout the length of tunnel except for one area of lapilli tuff near the u/s end. Widely spaced faults cut the rock normal to tunnel axis & closely spaced jts. occur in rock d/s of transition section. The faults are nearly vertical & the joints are nearly horizontal. Drill & blast by top heading & bench & presplitting at the portals produced excellent results - an outstanding example of good blasting procedures. Support by steel sets, in transition & horseshoe sections at u/s end. Rockbolts used in tunnel crown thruout w/a small amount of mesh to prevent fallouts where sealing did not eliminate the problem.
None		None	None	534'	$ 390.00 w/o ribs or rock bolts	Fm. not given. Andesite, hard, massive w/few scattered fractures. Soft, weathered rock at u/s portal resulted in cut-cover section. An intersection of 2 major faults at d/s portal resulted in several rock slides requiring careful excavation & timbering at the portal. Drill & blast.
None		None	None	925'	$1130.00	Volcanics, Tertiary and Quaternary. Felsite at both portals. Tunnel thru tuffs, basalts and volcanic glass based on logs of borings along tunnel alignment. No tunnel geology given. Steel supports. Drill and blast. No water problems.
None		None	None	758'	N. A.	Granitic rocks, with thin dikes of alpite and pegmatite. Quality of granite varied from fresh and sound to highly weathered and altered. The granite is moderately jointed, with joints 2 to 8 feet apart with occasional shear zones and faults. Drill and blast, 8' pulls w/modified "pyramid cut". Tunnel support by steel "I" beams with arched cross braces in the transitions to the shaft.

LINE NO.	CONSTRUCTED BY C. OF E. DISTRICT	PROJECT & APPROX. DATE DESIGN AND CONSTRUCTION	FINISHED DIAMETER	TUNNEL TYPE	TUNNEL SECTION	TEMP SUPPORTS	SUPPORT SPACING	MAX. DESIGN HEAD	CONC. LINING THICK.	fc' P.S.I.	LONG. STEEL	HOOP STEEL	AREA OF STEEL/FT.
102	Seattle	Libby (1969) Reservoir Flathead Tunnel	18' wide 25' high	Railroad	Modified Horseshoe	Steel Sets	Varied 2' to 6'	Not Applicable	18"	3500	Min.	Min.	
103	Mobile	Carter's Dam (1969) Georgia	18'	Penstock	Circular	W8 x 17	4'	341' - 578'	2'-6"	3000	None	None	
104	Mobile	Carter's Dam (1972) Georgia	16'	Emergency Low-Level Sluice	Circular and Horseshoe	W8 x 20	4'	519'	1"-6" (Min.)	4000	Varies	Varies	Varies

fc' P. S. I.	LONG. STEEL	HOOP STEEL	AREA OF STEEL/FT.	STEEL LINER THICK.	SPACING OF BLOCKING POINTS	TUNNEL LENGTH	EST. COST PER LINEAR FOOT	GEOLOGICAL CONDITIONS ENCOUNTERED
3500	Min.	Min.		None		7.0 mi.		Metasediments of the Precambrian (Belt Series) consisting of argillite, quartzite and numerous fault zones with breccia and gouge. A support problem was encountered when crossing the hanging wall of one of the faults. At least three sets of prominent joints were encountered including bedding plane joints. Joint spacing varied causing blockiness and resulted in a sawtooth appearance in some reaches of the tunnel. Instrumentation measurements were made using prop load cells and extensometers. The tunnel was excavated by drill and blast. No serious water problems. Average wall and arch concrete placing rates exceeded 1,700 cubic yards per day, which resulted in a major cost savings.
3000	None	None		5/8" to 1 3/4"	4'	837'	$958	Similar formations as encountered at Carter's Diversion Tunnels as shown on Line No. 90, Appendix F, Plate 6.
4000	Varies	Varies	Varies	None	4'	1080' (Circular) 1439' (Horseshoe)	$673	Similar formations as encountered at Carter's Diversion Tunnels as shown on Line No. 90, Appendix F, Plate 6.

U. S. Tunnels Summary
from "A Brief Survey of Recent Tunnel Construction
by U. S. Contractors," P. E. Sperry (1982)

Year	No. of Tunnel Contracts	Cumulative Bid Price, $ millions	Inflation Factor*	Cumulative Bid Prices, Updated to 1982 Dollars
1977	21	1266	1.54	1951
1978	24	848	1.45	1230
1979	13	533	1.34	714
1980	10	679	1.21	822
1981	5	264	1.09	288
1982	8	792	1.00	792

Total Period = 6 years

Total Cumulative Bid Prices
in 1982 dollars = $5,797

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* Inflation factors used are taken from Engineering News Record, March 18, 1982, and are from the U. S. Bureau of Reclamation's cost figures for water and power construction projects in 17 western states.

U. S. Tunnel Contracts Awarded In 1977

Project	State	Project Type	Ground Type	Excavation Method	Excavated Diam, ft	Length ft	Bid Price 10^6 dollars
Balto Subway	Md.	Tunnel-rapid transit	Overburden	Shield	19	3,000	17
Balto Subway	Md.	Tunnel-rapid transit	Crystalline rock	Mechanical	19	13,000	40
Bath Co	Va.	Tunnel-power	Sedimentary rock	Mechanical	10	2,000?	15E*
Helms	Calif.	Tunnel-cavern Tunnel-power	Crystalline rock	Drill and blast	31	22,000	381
Chicago 73-287	Ill.	Tunnel-sewer	Sedimentary rock	Mechanical	21	47,000	79
WMATA A-9B	D.C.	Cavern-rapid transit	Crystalline rock	Drill and blast	30	1,000	61
Peachtree Creek	Ga.	Tunnel-sewer	Crystalline rock	Drill and blast	10	9,000	5E
Chicago 70-229	Ill.	Tunnel-sewer	Overburden	Mechanical	8	20,000	7
Park River	Conn.	Tunnel-drain	Crystalline rock	Mechanical	24	9,000	23
Chicago 73-160	Ill.	Tunnel-sewer	Sedimentary rock	Mechanical	35	19,000	86
Red Hook	N.Y.	Tunnel-sewer	Overburden	Mechanical	10	9,000	85
Chicago 75-126	Ill.	Tunnel-sewer	Sedimentary rock	Mechanical	35	26,000	99
Stanford Accel	Calif.	Tunnel-other	Sedimentary rock	Mechanical	13	2,000	13
Kelly Is	N.Y.	Tunnel-sewer	Sedimentary rock	Drill and blast	10	1,000	5
Miners Ranch	Calif.	Tunnel-water	Crystalline rock	Mechanical	10	4,000	4
Chicago 75-125	Ill.	Tunnel-sewer	Sedimentary rock	Mechanical	32	25,000	108

(Continued)

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* E = estimated.

U. S. Tunnel Contracts Awarded In 1977 (Concluded)

Project	State	Project Type	Ground Type	Excavation Method	Excavated Diam, ft	Length ft	Bid Price 10^6 dollars
Atlanta	Ga.	Tunnel-cavern Tunnel-rapid transit	Crystalline rock	Drill and blast	20	8,000	43
Chicago 75-124	Ill.	Tunnel-sewer	Sedimentary rock	Mechanical	32	20,000	102
Aqua Fria	Ariz.	Tunnel-water	Crystalline rock	Drill and blast	22	6,000	14
Back River	S.C.	Tunnel-water	Overburden	Mechanical	10	5,000?	2E
Balto Subway	Md.	Tunnel-rapid transit	Crystalline rock	Drill and blast	20	18,000	41
Balto Subway	Md.	Tunnel-rapid transit	Crystalline rock	Drill and blast	20	5,000	36

Number of Projects = 22

Cumulative Bid Price for 22 Projects
Awarded in 1977 = $1,266 million

Cumulative length = 292,000 ft
= 55.3 miles

U. S. Tunnel Contracts Awarded In 1978

Project	State	Project Type	Ground Type	Excavation Method	Excavated Diam, ft	Length ft	Bid Price 10^6 dollars
Chicago 75-123	Ill.	Tunnel-sewer	Sedimentary rock	Mechanical	32	23,000	85
Balto Subway	Md.	Tunnel-sewer	Crystalline rock	Drill and blast	20	2,000	36
Storm Drain	Minn.	Tunnel-drain	Overburden	Shield	10	10,000	9
WMATA A-11B	Md.	Cavern-rapid transit	Crystalline rock	Drill and blast	30	1,000	23
Applegate	Oreg.	Tunnel-power	Crystalline rock	Drill and blast	18	4,000	8E*
Warm Springs	Calif.	Tunnel-power	Sedimentary rock	Drill and blast	15	3,000	5E
Porter Pilot	Mass.	Tunnel-rapid transit	Sedimentary rock	Drill and blast	12	1,000	2
Alpine	Utah	Tunnel-water	Sedimentary rock	Drill and blast	10	2,000	3
Scajaquada	N.Y.	Tunnel-sewer	Sedimentary rock	Mechanical	10	27,000	29
WMATA A-11C	Md.	Cavern-rapid transit	Crystalline rock	Drill and blast	30	1,000	21
NYCTA #131-A	N.Y.	Tunnel-rapid transit	Crystalline rock	Mechanical	21	6,000	186
North Int.	Mich.	Tunnel-sewer	Overburden	Mechanical	16	16,000	37
Haryard-Porter	Mass.	Tunnel-rapid transit	Sedimentary rock and overburden	Drill and blast and shield	21	5,000	47
Buffalo C-31	N.Y.	Tunnel-rapid transit	Sedimentary rock	Mechanical	19	15,000	35
Pacheco 2	Calif.	Tunnel-water	Sedimentary rock	Drill and blast	12	28,000	50

(Continued)

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* E = estimated.

U. S. Tunnel Contracts Awarded In 1978 (Concluded)

Project	State	Project Type	Ground Type	Excavation Method	Excavated Diam, ft	Length ft	Bid Price 10^6 dollars
WSSC/W	Md.	Tunnel-water	Crystalline rock	Mechanical	12	15,000	21
Buffalo C-11	N.Y.	Tunnel-rapid transit	Sedimentary rock	Mechanical	19	21,000	39
Porter-Davis	Mass.	Tunnel-rapid transit	Sedimentary rock	Drill and blast	21	5,000	24
Pocahontas	W.Va.	Tunnel-mine	Sedimentary rock	Drill and blast	13	4,000	4E
R&P Coal	Pa.	Tunnel-mine	Sedimentary rock	Mechanical	12	1,000	2E
WMATA C-10A	Va.	Tunnel-rapid transit	Overburden	Mechanical	19	1,000	17
NYCTA	N.Y.	Tunnel-cavern	Crystalline rock	Drill and blast	54	1,000	154
WSSC W-80	Md.	Tunnel-water	Crystalline rock	Mechanical	10	5,000	5
Bueliah	N.Dak.	Tunnel-power	Sedimentary rock	Mechanical	10?	2,000?	7E

Number of Projects = 24

Cumulative Bid Price for 24 Projects
Awarded in 1978 = $848 million

Cumulative length = 199,000 ft
= 37.7 miles

U. S. Tunnel Contracts Awarded In 1979

Project	State	Project Type	Ground Type	Excavation Method	Excavated Diam, ft	Length ft	Bid Price 10^6 dollars
Chicago 69-206	Ill.	Tunnel-sewer	Sedimentary rock	Drill and blast	10	12,000	10
Chicago 73-162	Ill.	Tunnel-sewer	Sedimentary rock	Mechanical	14	37,000	65
3 Rivers	Ga.	Tunnel-sewer	Crystalline rock	Mechanical	13	40,000	32
Chicago 74-206	Ill.	Cavern-sewer	Sedimentary rock	Drill and blast	60	<1,000	55
Chicago 73-162	Ill.	Cavern-sewer	Sedimentary rock	Drill and blast	18	13,000	28
San Francisco/N-1	Calif.	Tunnel-sewer	Sedimentary rock	Mechanical	12	4,000	10
Green Lake	Alaska	Tunnel-power	Crystalline rock	Drill and blast	15	3,000	27
WSSC/E	Md.	Tunnel-water	Crystalline rock	Mechanical	12	18,000	22
Foothills	Colo.	Tunnel-water	Crystalline and sedimentary rock	Drill and blast	13	18,000	23
San Francisco/N-2	Calif.	Tunnel-sewer	Overburden	Mechanical	17	3,000	13
Little Blue	Mo.	Tunnel-sewer	Sedimentary rock	Mechanical	12	32,000	35
Chicago 73-162	Ill.	Cavern-sewer	Sedimentary rock	Drill and blast	75	<1,000	169
Porter Square	Mass.	Cavern-rapid transit	Sedimentary rock	Drill and blast	40	<1,000	44

Number of Projects = 13

Cumulative Bid Price for 13 Projects Awarded in 1979 = $533 million

Cumulative length = 183,000 ft
= 34.7 miles

U. S. Tunnel Contracts Awarded In 1980

Project	State	Project Type	Ground Type	Excavation Method	Excavated Diam, ft	Length ft	Bid Price 10^6 dollars
Fort McHenry	Md.	Tunnel-highway	Overburden	Tube	30	9,000	426
Kerckhoff 2	Ca.	Tunnel-power cavern	Crystalline rock	Mechanical and drill and blast	24	22,000	55E*
WMATA B-9A	Md.	Tunnel-rapid transit	Crystalline rock	Drill and blast	20	12,000	77
Hades and Rhodes	Utah	Tunnel-water	Sedimentary rock	Mechanical	10	26,000	35
NYCTA #131-D	N.Y.	Tunnel-rapid transit	Crystalline rock	Drill and blast	19	2,000	35
Milwaukee #289	Wis.	Tunnel-sewer	Sedimentary rock	Mechanical	9	11,000	11
Milwaukee #287	Wis.	Tunnel-sewer	Sedimentary rock	Mechanical	9	11,000	14
Milwaukee #288	Wis.	Tunnel-sewer	Sedimentary rock	Mechanical	9	13,000	14
Milwaukee	Wis.	Tunnel-sewer	Sedimentary rock	Mechanical	10	6,000	5
Milwaukee	Wis.	Tunnel-sewer	Sedimentary rock	?	9	6,000	7

Number of Projects = 10

Cumulative Bid Price for 10 Projects
Awarded in 1980 = $679 million

Cumulative length = 118,000 ft
= 22.3 miles

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* E = estimated.

U. S. Tunnel Contracts Awarded In 1981

Project	State	Project Type	Ground Type	Excavation Method	Excavated Diam, ft	Length ft	Bid Price 10^6 dollars
Santa Clara	Calif.	Tunnel-water	Sedimentary rock	Mechanical	12	5,000	9
Rocky Mountain	Ga.	Tunnel-power	Sedimentary rock	Drill and blast	30	4,000	25
Tumbler Ridge	B.C.	Tunnel-railroad	Crystalline rock	Drill and blast	24	50,000	200E*
McDowell Extension	S.C.	Tunnel-water	Overburden	Mechanical	9	11,000	2
Strawberry	Utah	Tunnel-water	Sedimentary rock	Drill and blast	13	3,000	11
Sultan	WN	Tunnel-power	Crystalline rock	Mechanical	14	21,000	17

Number of Projects = 6

Cumulative Bid Price for 6 Projects
Awarded in 1981 = $264 million

Cumulative length = 94,000 ft
= 17.80 miles

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* E = estimated.

U. S. Tunnel Contracts Awarded In 1982

Project	State	Project Type	Ground Type	Excavation Method	Excavated Diam (ft)	Length (ft)	Bid Price 10^6 dollars
Delores	Colo.	Tunnel-water	Sedimentary rock	Mechanical	12	7,000	12
Stillwater Compl.	Utah	Tunnel-water	Sedimentary rock	Mechanical	10	29,000	30E*
Crosstown	D.C.	Tunnel-water	Crystalline rock	Mechanical	11	13,000	13
Lyell Ave	N.Y.	Tunnel-sewer	Sedimentary rock	Mechanical	12	11,000	16
Terror Lake	Alaska	Tunnel-power	Crystalline rock	Drill and blast	12	26,000	50E
Saxton-C/J-A	N.Y.	Tunnel-sewer	Sedimentary rock	Mechanical	10	12,000	36
Mount Baker	WN	Tunnel-highway	Overburden	?	63	1,000	80E
Selkirk	B.C.	Tunnel-railroad	Sedimentary rock	Drill and blast	24	48,000	550E
Red Mountain	Ala.	Tunnel-sewer	Sedimentary rock	?	9	5,000	5E

Number of Projects = 9

Cumulative Bid Price for 9 Projects
Awarded in 1982 = $792 million

Cumulative length = 152,000 ft
= 28.8 miles

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* E = estimated.

Cost and Performance Data for Roadheader and Cutting Boom Tunnels Reported by Anderson Mavor (Manufacturer)

A: Anderson Mavor roadheaders in civil engineering

1: ITALY

Model RH1W –	Motorway service tunnel.
Tunnel	5.0 metres wide by 5.3 metres high
Rock	Mudstone, shale, siltstone – 650 kg/cm^2
Drivage	900 metres at 7.0 metres per day, average
Picks	1 pick per 20 cubic metres
Loading	via two bridge conveyors into rail cars of 5 cubic metres capacity
Support	Arches, 2.0 metres setting + Guniting (6–8 cms)
Ventilation	Exhausting

2: ITALY

Model RH1C –	Motorway tunnel (top half)
Tunnel	14.0 metres wide by 5.4 metres high (50 square metres)
Rock	Marl, shale, conglomerate – 480 kg/cm^2
Drivage	400 metres at 4.0 metres per shift (rock changed to hard limestone + 1.500 kg/cm^2
Picks	1 pick per 0.40 cubic metres
Loading	Front end loader direct from rear of roadheader and into lorries.
Support	Arch girders, 1.0 metre settings.
Ventilation	Forcing

Note: Roadhead took 3 parallel cuts to get the width and 2 vertical lifts in the centre (1 at 4.4 metres and 1 at 1.0 metres)

3: SICILY

Model RH1C –	Motorway tunnels (2) – top halves
Tunnel	14.0 metres wide by 4.7 metres high (46 square metres)
Rock	Clay (blue and stiff) 50 kg/cm^2
Drivage	700 metres (& continuing) 7.0 metres per day average, 35 metres per week. Machine excavation rate 70 cubic metres per hour.
Picks	1 pick per 200 cubic metres
Loading	Fiat FL11 front end loader direct into lorries (roadheader working without gathering system)
Support	Arch girders – 1.0 metre setting – Guniting
Ventilation	Forcing

Note: The roadheader drove 2.0 metres in one tunnel and flitted to the second tunnel to drive 2.0 metres whilst the first tunnel was supported.

4: SICILY

Model RH1C –	Mine addition
Tunnel	4.8 metres wide by 3.0 metres high
Rock	Clay, gypsum, anhydrite – varying hardness
Drivage	400 metres at 1 in 4 dipping

Picks	1 pick per 25 cubic metres
Loading	From roadheader into front end loaders and into skips
Support	Arches – lagged – 1.0 metres settings.
Ventilation	Exhausting

Note: The ground was very variable

5: JAPAN

Model RH1C	–	Motorway tunnel
Tunnel		Arch (top half) 11.0 metres wide by 5.5 metres wide (48 square metres)
Rock		Volcanic tufa (very abrasive but soft friable coarse grained) up to 150 kg/cm^2
Drivage		Continuing – 6.0 metres per day including arch setting
Picks		1 pick per 45 cubic metres
Loading		From roadheader onto bridge conveyor and into lorries
Support		Arches at 0.8 metres centres
Ventilation		Forcing

C: Anderson Mavor cutting booms

1: GREAT BRITAIN

Model –	Ripping or tunnel enlargement machine
Tunnels	Varying from 4.0 metres wide by 3.0 metres high to 5.0 metres by 4.0 metres
Rocks	Shales, siltstone, sandstone, mudstone up to 900 kg/cm^2
Drivages	Excavation rates up to 20 cubic metres per hour
Loading	Scraper buckets
Support	Arches – 0.9 metres settings (lagged)

Note: Over 70 of these machines are at work in rock

2: GREAT BRITAIN

Model –	49 kW telescopic cutting boom, turret mounted behind the tunnelling shield
Tunnel	4.1 metre diameter by 1720 metre long, tunnel for underground (Metro) railway
Rocks	Clay
Drivage	Rates of up to 22 metres per day, machine excavation rate of 40 cubic metres per hour
Loading	Gathering paddles, belt conveyor and bunker cars
Support	610mm wide concrete segmental rings, wedge blocked

3: ITALY

Model –	Three 49 kW cutting booms on hydraulic excavators
Three tunnels	Railway tunnels – 9.0 metres wide by 7.2 metres high (50 square metres)
Rock	Clay, sandstone
Drivages	Average of 110 metres per month over 14 months. Machine excavation rate 75 cubic metres per hour
Loading	Front end loaders, of 1.0 and 2.0 cubic metres capacity – around and in front of excavator, direct into lorries
Support	Arch girders at 1.0 metre intervals + Gunite

Note: Two booms mounted on Benati BAM200 hydraulic excavators (one on each and one on a link belt excavator.)

4: ITALY

Model –	49 kW cutting boom on Benati excavator
Tunnel	Motorway – 8.5 metres wide by 7.0 metres high
Rocks	Shale – 600 kg/cm^2
Loading	Front end loaders

5: GREAT BRITAIN

Model —	49 kW cutting boom, turret mounted on slides inside the tunnelling shield
Tunnel	3.5 metre diameter by 460 metres long sewer tunnel
Rocks	Coal measure strata of mudstone, siltstone and sandstone with occurring coal seams
Loading	Gathering arms, scraper chain conveyor, belt conveyor and trucks
Support	500mm cast iron bolted segmental rings

6: GREAT BRITAIN

Model —	49 kW cutting boom, gimbal mounted inside the tunnelling shield
Tunnel	2.8 metre diameter by 1220 metre long cable tunnel
Rocks	Clay
Drivage	Rates up to 22 metres per day
Loading	Scraper chain, belt conveyor and trucks
Support	610mm wide concrete smooth bore segmental rings, wedge blocked

7: GREAT BRITAIN

Model —	Two 49 kW cutting booms, gimbal mounted inside the tunnelling shield
Tunnel	2.88 metres diameter sewer tunnel
Rocks	Clay/limestone
Drivage	Rates up to 20 metres per day
Loading	Scroll on boom, scraper chain conveyor, belt conveyor and trucks
Support	610mm wide concrete bore segmental rings

8: GREAT BRITAIN

Model —	49 kW cutting boom, gimbal mounted inside the tunnelling shield
Tunnel	3.2 metre diameter sewer tunnel
Rocks	Shale/ironstone bands/coal measures
Loading	Scroll on boom, scraper chain conveyor and trucks
Support	610mm wide concrete bolted segmental rings

Cost and performance data for Kerckhoff 2 tunnel

9. Kerckhoff 2 Power Tunnel (Kennedy, 1982) a 24-ft, 1-in.-diam, 22,000-ft-long tunnel, was excavated through massive Sierra hard granite (maximum UC strengths were 24,000 psi and averaged 16,500 psi). Quartz content was about 25 percent, resulting in high abrasivity. Other pertinent details are listed below:

a. No lining was needed with TBM.

b. Only occasionally light support was installed.

c. No water and no faults were encountered.

d. Robbins and Auburn Constructors designed machine to be most reliable TBM designed to date. Dual oil lube systems, dual water spray dust control systems, special electrical circuits, etc., were incorporated.

e. The thrust/cutter was 45,000 lb and 57 cutters were used.

f. Total thrust was 1,282 tons.

g. Total power was 2,200 hp (11 each 200-hp electric motors).

h. Boring stroke was 6 ft.

i. Cutterhead speed was 5.8 rpm.

j. Actual advance rates achieved were:

Average, 62-70 ft/day
Range, 38 to 137 ft/day

k. The working day was 2 10-hr shifts plus 4 hr for maintenance.

l. Fifteen hundred feet were driven in first 29 days.

m. Actual use was 12.5 hr/day for first 28 days.

n. Availability was near 70-85 percent (availability is percentage of time the machine is ready to bore, as compared to the shift hours worked).

o. Penetration rates ranged from 4-5 ft/hr while machine was being used.

p. Cutter loads have run from 45,000-53,000 psi each.

Other important points

10. Effects of cutter sharpness on penetration were studied on this job. Results were that sharpness did not affect cutting for applied thrust up to 25,000 psi per cutter. But above 25,000 psi per cutter, new, sharper cutters significantly increased penetration rates over the dulled ones.

Thrust/ Cutter	Penetration, in.		Improvement sharp over dull, percent
	Sharp	Dull	
30,000 lb	0.125	0.088	+42
36,000 lb	0.190	0.133	+43
42,000 lb	0.270	0.163	+66

These results have provided good reasons to push development of improved cutter materials and optimum profiles.

TARP Contracts Performance Data

Contract	Contractor	Manufacturer	Diam Ft-In	Tunnel Length lin ft	Tunnel Bored Lf	Fin %	Hour Avg.	Hour Best	Shift Avg.	Shift Best	Day Avg. Lineal	Day Best Feet	Week Avg.	Week Best	Month Ave.	Month Best	Labor Job man-hours/lin ft	Labor Job man-hours/yd^3	Mach Efficiency %
73-160-2H	M/K-Kenny-Paschen-S&M	Robbins	35-4	17744	17744	100	5.2	10.0	21.6	49.0	61.0	118.0	291	472	1183	1809	9.92	0.273	53.4
73-162-CH	M/K-Paschen	Robbins	35-4	2931	2931	100	5.1	7.0	22.6	43.0	62.4	104.0	293	442	733	1417	9.46	0.260	55.6
75-126-2H	Healy-Ball-Horn	Robbins	35-3	25358	19951	77	6.0	14.3	18.4	44.3	54.8	120.1	270	529	1108	1789	8.17	0.226	38.5
75-125-2H	Paschen-M/K-Kenny	Jarva	32-3	24692	24692	100	6.9	13.4	16.8	58.5	47.9	146.2	274	611	1074	2252	11.71	0.387	30.3
75-124-2H	Kiewit-Shea-Shea	Robbins	32-4	13052	13052	100	5.7	12.5	20.1	53.0	58.3	143.0	278	542	1088	1881	7.49	0.246	43.7
75-123-2H	Ball-Healy-Horn	Robbins	32-4	21922	21922	100	5.9	10.0	24.1	52.0	65.1	136.0	354	600	1370	2024	7.38	0.243	51.5
72-049-2H	Kenny-Paschen-S&M	Jarva	30-1	27269	27269	100	6.2	15.0	18.7	60.0	55.2	167.0	270	637	1091	2461	5.51	0.209	38.0
72-049-2H	Kenny-Paschen-S&M	Jarva	22-1	24036	24036	100	6.2	16.0	22.8	67.0	67.7	173.0	316	734	1265	2194	4.28	0.302	45.9
73-317-2S	Healy-Ball-Greenfield	Robbins	22-1	22061	22061	100	3.0	8.3	25.2	66.0	75.6	150.0	378	640	1637	2147	2.96	0.590	38.0
73-287-2H	Traylor-Ferrera-Resco	Robbins	21-3	42540	31352	74	6.5	18.8	23.5	71.0	68.8	188.5	334	774	1254	2612	6.61	0.505	47.3
73-320-2S	James McHugh Const Co	Robbins	18-2	10670	10670	100	4.7	9.6	37.2	63.0	76.2	159.0	381	589	1650	2183	4.65	0.420	71.0
75-124-2H	Kiewit-Shea-Shea	Jarva	15-3	6869	6869	100	5.9	30.0	14.3	41.0	37.5	100.0	196	410	763	1425	12.67	1.872	31.0
73-162-BH	Healy-Ball-Grow	Robbins	14-2	36471	24846	68	12.4	17.7	45.4	100.0	126.1	265.0	565	1033	2258	4063	3.66	0.627	45.6
73-287-2H	Traylor-Ferrera-Resco	Special	9-0	5515	5011	91	2.8	6.9	11.3	33.5	18.9	59.0	93	234	334	726	8.07	3.441	48.1
69-206-2S	Kenny-Jay/Dee	Robbins	8-9	11755	11755	100	7.5	19.5	26.4	93.0	48.0	154.0	226	495	904	1599	5.06	2.271	38.8
71-703-2S	Kenny-Jay/Dee-Jay/Dee	Jarva	6-6	17640	9163	52	8.5	11.9	41.3	81.0	72.2	153.0	327	601	1145	2151	2.76	2.244	52.9

TOTALS = 310525' 273324' 88.02%
58.8MI 51.8MI
94.6KM 83.3KM

Notes:
1. Labor (man-hours per cubic yard) = Total man-hours divided by total solid volume bored.
2. Machine Efficiency (%) = Operating hours divided by operating hours + down hours multiplied by 100.
3. Bored length does not include tunnel blasted to install mining machine.

Courtesy of
Metropolitan Sanitary District
of Greater Chicago
Tunnel and Reservoir Section
Date of Last Entry 4/17/81

W.J.W. 04-May-81

TARP Project Tunnels

11. One of the largest tunneling jobs currently under way is in progress in Chicago, Ill. (Tunnels and Tunneling, 1980). The Chicagoland Tunnel and Reservoir Plan will comprise 131 miles of tunnels (drilled principally through silurian dolomitic limestone some 150 to 300 ft below the surface), 251 vertical drop shafts, 645 near-surface collecting structures, four pumping stations, and 155 million m^3 of storage in five reservoirs.

12. The contractor chose to use TBM's for the tunneling instead of the drill and blast method. This was done for the following reasons: (a) surrounding ground is not disturbed which minimizes tunnel support, (b) rock falls are reduced, and (c) TBM's are estimated to be 4 to 6 times faster.

13. A Java Mk. 30 is being used by Paschen/Morrison-Knudsen/Kenny joint venture. The Mk. 30 cutting wheel is powered by sixteen 150-hp electric motors. Transformers on the training gear convert the 13,200 v, which is fed down the tunnel, to 480 v for operation of the machine.

14. The Mk. 30 is boring approximately 80 m below the surface, at an average rate of over 24.4 m/day on a three-shift basis. Best progress so far per 8-hr shift has been 18.29 m; per 3-shift day, 46.03 m; and per 5-day week, 194.46 m. The machine's availability is over 80 percent, the few stoppages are due to electrical or hydraulic problems but utilization works out at some 40 to 50 percent when stoppages for other reasons are considered.

15. On this contract, muck is loaded by an 18-car trailing gear system designed by Zokor Corporation which features 51 m of stationary conveyor working in conjunction with a car passer mechanism which allows the muck to be moved from the empty car-in-rail to the full-car-out rail. The trailing gear loads six muck trains, each consisting of seven 708-litre muck cars and pulled by 215-hp Plymouth locomotive.

16. Maximum haul distance is 4977 m to a roller dump station where muck is deposited on an inclined conveyor by way of a shaker, grizzly, and rock crusher. The variable speed inclined conveyor places the muck on the horizontal portion of a vertical conveyor made by Conrad Scholtz of Hamburg. This vertical conveyor consists of a 198.42-m continuous reinforced flexowall rubber belt, the first of its kind in the world, capable of removing up to 907 tonnes/hr. The 510 performed rubber pockets on the 1.6-m-wide belt carry the payload at the rate of 137 m/min. (The maximum life for a flexowall belt

would be 183 m and the maximum capacity would be 2000 m^3/hr.) The entire mucking out system on this site is designed to match an average TBM advance of 3.05 m/hr or the equivalent of 230.9 m^3/r of muck with a maximum capacity of 344 m^3/hr.

17. Contractor Morrison-Knudsen's (M-K) 35 ft, 4-in. Robbins Tunnel Boring Machine (TBM) recently holed through on Chicago's Tunnel and Reservoir Plan (TARP) project to complete the world's largest diameter hard rock tunnel (Tunnels and Tunneling, 1980). In a joint venture with Kenny Construction, Paschen Contractors, and S&M Constructors, Morrison-Knudsen drove the big 810-ton machine through 17,744 ft of dolomitic limestone in 383 days, or an average advance of 46.3 ft/24-hr day.

18. Several performance records were established by the Robbins machine, e.g., the new excavation records for a single shift (1743 yd^3) and in a 24-hr period (4285 yd^3). The TBM averaged 57 percent availability during the entire job.

19. This is just one of the tunnels in the 141 miles of planned tunnels that will be driven in the TARP project. Robbins Company has a 34-ft, 4-in. TBM, a 35-ft TBM, two 32-ft TBM's, four smaller TBM's, and two large shaft boring machines working on the TARP project.

Data for Solk power tunnel

20. Wagner (1979) reported on the construction of the Solk power station in Austria. This 7.2-mile-long by 10.8-ft-diam tunnel was constructed using a Robbins mole and rail muck haulage. The 600-hp mole used 29 single discs rotated at 7.2 rpm. The machine stroke was 3.65 ft. For this long tunnel, average daily advance was 66 ft/day. Much thought went into the muck removal train design. Special precast invert segments were used to provide a very stable track bed and eliminate derailments and increase operating speed. The train was operated at about 9 mph and switching was well coordinated.

Comparison of Robbins and Demag TBM's

21. Two types of TBM's, the Robbins 123/133 and the Demag TVM 34-38, were compared by McFeat-Smith and Tarkoy (1979). Developments in cutterhead technology have enabled TBM's to be used in hard rock.

22. The Robbins machine is 8 years old; newer models may give better statistics. The Robbins machine had single discs and the Demag had triple discs. The single discs performed better. See Tables 1 and 2 for breakdown analysis of Demag and Robbins machines.

Table 1

Breakdown analysis—percentage shift time

Demag TVM 34–38 triple disc/button

		Rock Type	Sandstone	Sandstone	Mixed beds	Mudstone	Limestone	Dolerite (Buttons)	Mudstone
		Condition	Siliceous	Siliceous	Hardened	Silty	Massive	Competent	Pure
		Distance from portal (km)	0–0.5 Learning period	0.5	1	2	2	3	5
		Test length (m)	500	200	450	150	850	200	100
		Penetration (m/hr)	1.2	1.2	1.6	2.0	1.4	0.6	2.7
ESSENTIAL DELAYS	1	Machine maintenance	2.7	4.1	7.8	11.5	11.8	10.7	11.6
	2	Cutter replacement	10.0	10.2	2.7	1.0	4.2	11.2	1.9
	3	Track/invert units	6.7		1.8	2.4	2.3		2.4
	4	Support	1.7		6.4	12.2	1.0	0.1	22.1
	5	Laser/survey	0.2					0.9	
	6	Services	1.8	0.2	3.4	3.5	4.9	1.1	8.4
	7	Changeover trains	2.3	3.4	6.2	3.7	6.0	2.5	7.8
NON-ESSENTIAL DELAYS	8	Chutes	4.1	4.6	1.6	5.7	2.1	1.0	10.9
	9	Conveyor	16.7	8.8	5.3	5.9	0.1	5.5	2.7
	10	Machine conveyor	3.0	4.5		4.1			2.6
	11	Machine electrical	1.0	1.9	2.0	2.0	1.8	1.4	0.9
	12	Machine mechanical	4.3	7.7	9.9	3.5	1.1	0.7	1.1
	13	Previous supports						0.4	
	14	Train derailments	2.3	0.6	0.4	0.5	0.1	1.0	2.0
	15	Water (non-conveyor)	2.8	0.2	0.2				
	16	Tunnel maintenance				3.1	2.8	5.4	4.8
	17	External	2.6	1.3			0.7	0.3	
	18	Miscellaneous	6.0	4.2	2.0	2.7	5.0	9.9	3.5
		Machine utilisation	31.8	48.3	50.3	38.2	56.1	47.9	17.0
		Progress m/120 hr wk	45.8	69.6	96.6	91.7	94.2	34.5	55.1

Table 2

Breakdown analysis—percentage shift time

Robbins 123/133

		Rock Type	Sandstone	Limestone roof	Sandstone	Sandstone	Mudstone	Mudstone
		Condition	Massive, gritty	Mixed beds in tunnel	Siliceous	Gritty Shaley	Silty	Pure
		Distance from portal (km)	0.5	3	4.5	5.5	7	7.5
		Test length (m)	200	560	100	750	210	170
		Penetration (m/hr)	3.5	3.0	2.3	3.7	2.9	3.0
ESSENTIAL DELAYS (length dependent)	1	Machine maintenance	4.0	13.2	3.8	8.8	4.4	6.3
	2	Cutter replacement	6.5	9.1	11.0	5.4	2.1	2.7
	3	Track/invert units	0.3	1.8	2.0	2.4	0.7	6.8
	4	Support	0.9	2.1		6.9	17.7	28.8
	5	Laser/survey			*0.9			
	6	Services	4.9	5.4	3.0	3.4	5.5	2.4
	7	Changeover trains	14.6	15.0	13.5	16.0	8.7*	6.1*
NON-ESSENTIAL DELAYS	8	Chutes (Mucking)						
	9	Conveyor (Mucking)	0.6	0.3		1.5	0.9	1.1
	10	Machine conveyor (Mucking)						
	11	Machine electrical	3.8			0.3	1.4	1.6
	12	Machine mechanical	0.9	2.0	4.2	2.3	1.7	2.5
	13	Previous supports		1.2	2.0	1.1	3.7	
	14	Train derailments		0.7	4.0	2.6	1.5	3.2
	15	Water (non-conveyor)	26.2			0.5	1.3	
	16	Tunnel maintenance						
	17	External						
	18	Miscellaneous	9.2	10.1	12.6	13.8	14.4	15.6
		Machine utilisation	28.1	39.1	43.0	35.0	36.0	22.9
		Progress m/120 hr wk	118.0	140.8	118.7	155.4	125.3	82.4

*Train with larger mucking capacity introduced.

New York City Transit Authority stacked tunnels

23. Hard rock boring bid for New York City Transit Authority at $186 million beat drill and blast by $6.5 million. Two of the four tunnels are 20 ft 2 in. and 1455 ft long; the other two are 22 ft and 1320 ft long (Engineering News Record, 1981).

24. The rock is schist, said to be of fair quality but unpredictable, as the TBM drives the tunnel workers used a built-in erector to place steel rings 4 ft apart, with additional support provided by rock bolting where need, the upper two tunnels required shotcrete support, but this was not necessary for the remaining lower tunnels. The rock was more sound and the lined tunnels above may have contributed to the lower roof's stability. Penetration rates for the first tunnel averaged 20.5 ft/day and for the second tube, 26.4 ft/day. Progress in the larger third tube averaged 24.3 ft/day.

25. After finishing a bore, the mole was either disassembled to start a bore in another direction or backed out to start a bore in the same direction; resetting time varied from 1-1/2 to 2 months.

26. Muck haulage methods under consideration were car and truck versus Wagner Scooptram and Teletram methods. The short haul distances and the elimination of downtime by stand-by vehicles argued in favor of rubber-tired haul vehicles rather than car and truck. A Lake Shore banker system including conveyor and holding bin (35 tons) is attached to the TBM. The Teletram (25-ton capacity) is used to haul muck out of the tunnel to a holding area. The Teletram averages 80 percent availability and is backed up by the Scooptram. The TBM capacity is 2.5 m^3/min of muck and the muck handling system can accommodate 2.6 m^3/min. The Teletram hauls average 2.8 m^3/min with a cycle of 4.34 min at 408.4 m (one way).

Alpine tunnel

27. One hundred and sixty kilometres south of Salzburg in the Syrian Alps lies the Bodendorf Hydro Power Project. The 9.48-km tunnel runs from a secondary catch basin, the Kleinspoicher Paal, into the Bodendorf Generating Station. The 3.15-m-diam tunnel is to carry water at the rate of 10 m/sec. The project was commissioned by STEWEAG (Steirische Wasserkraftweke and Elektrizitats AG), a local Government-owned organization. The contractors for the joint venture are Austrian companies Hinteregger Und Solhne of Salzburg and C. Hinteregger of Brenzenz. The $6 million contract included the 9.5-m tunnel with lining access tunnels and surge tank.

28. The geology of the 530- to 300-m overburden consists of quartzite, shale, sandstone, phylites, and mica schists with average compressive strength of 1400 to 1800 kg/cm^2.

29. The contractor is using a 100-ton 3.55-m-diam Robbins Series 120 TBM fitted with 29 disc type cutters. The discs average life is 15 linear metres. Cutterhead operating thrust was 428 tons, but the machine is capable of thrusts up to 506 tons. The machine's hydraulic pressure has a maximum working pressure of 4200 psi operated by 65-hp pumps running two 11-hr shifts of 9 men each shift. The maximum rate in a 3000-m portion of the tunnel was 47 m/day. The average daily rate was 26 m reflecting lost time due to a maximum of 60 litre/second water ingress at one point in the tunnel. The TBM had to negotiate a 200 m length of tunnel with a 300-m radius which it accomplished with no problem. The experienced machine tunnelers stated that the Robbins TBM had a steering design simpler than many and referred to it as "the work horse of the TBM Stable."

30. The contractors were pleased with the rapid cutting of the TBM and felt it was important to be able to move the muck as rapidly as possible, so he chose a LEWA continuous mucking system by Envil Lechner, Inc., of Furich, Switzerland. The system was comprised of nine 5-m^3-capacity LEWA 5000 cars and a battery locomotive. Track is laid on the precast concrete segments. The double track behind the Robbins TBM is served by one man operating a chain pulling device to position the empty cars. The cars are unloaded automatically at a tipping bridge, and the train moves continuously at 1 m/sec even during dumping. The motion of the train during dumping is described as smooth.

Case Histories Reported by the Bureau of Reclamation

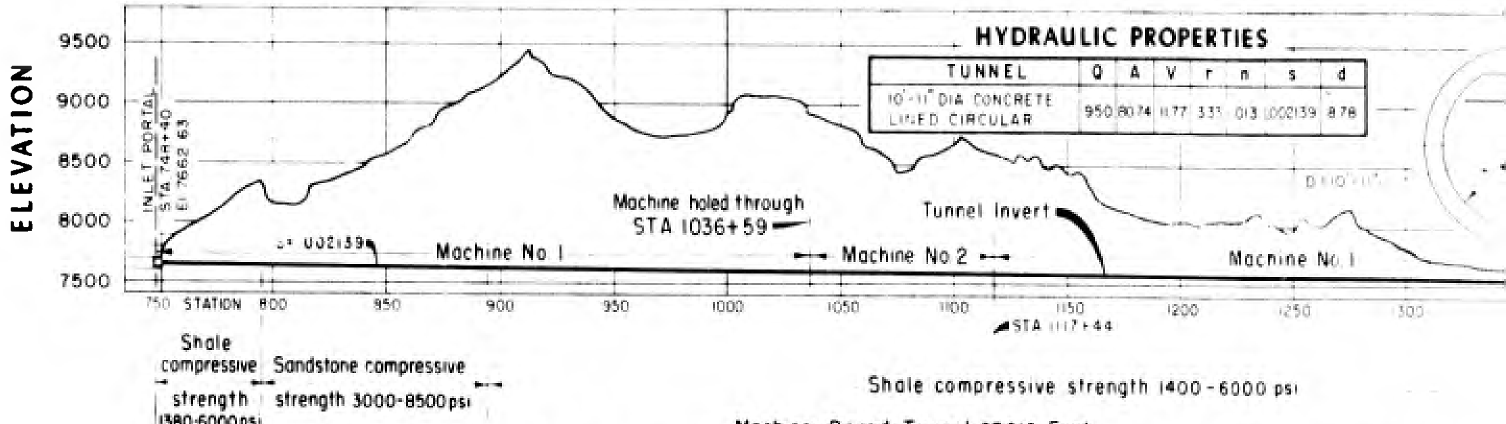
31. The following eleven pages are from Report Number REC-ERC-74-7 entitled Tunnels by The United States Department of the Interior, Bureau of Reclamation, Engineering and Research Center, Office of Design and Construction, Denver, Colo., 1974.

AZOTEA

SAN JUAN C

COLORAD

TUNNEL PROFILE



HYDRAULIC PROPERTIES

TUNNEL	Q	A	V	r	n	s	d
10'-11" DIA CONCRETE LINED CIRCULAR	950	80.74	11.77	3.33	.013	.002139	8.78

Shale compressive strength 1380-6000psi

Sandstone compressive strength 3000-8500psi

Shale compressive strength 1400-6000 psi

Machine Bored Tunnel 67,010 Feet

Diameters Bored 12'-8"; 12'-6"; 13'-4" 100% Supported 36.3% Structural Steel Ribs 63.7% Rock Bolts and Metal Shapes

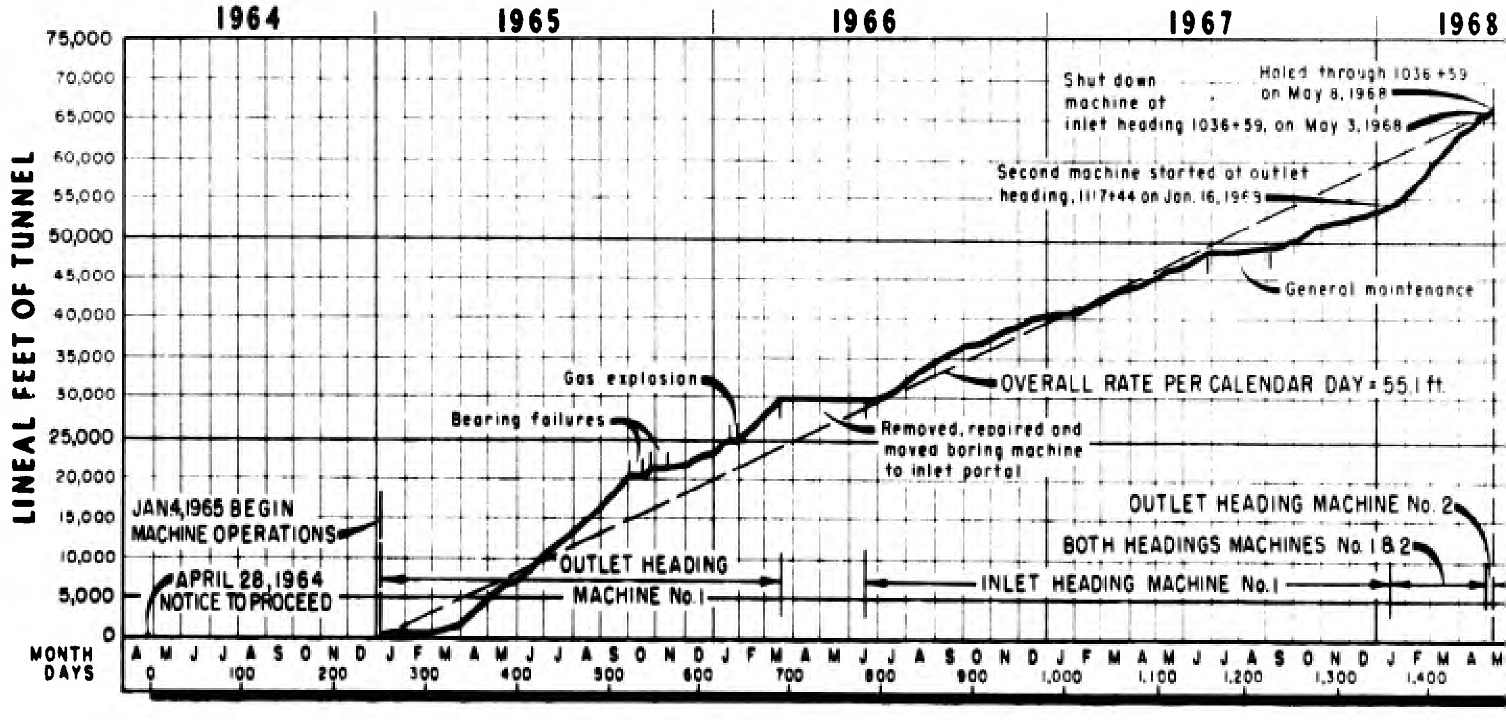
MACHINE DATA (MACHINE No.1)

MANUFACTURED BY ROBBINS MODEL 104-121A
LENGTH---------35 FT. WEIGHT-152,200 LBS.
*THRUST--- 477,000 LBS. *TORQUE 300,000 FT. LBS.
CUTTERS---25 or 29 DISC, 1-TRICONE IN CENTER
ROTATION BY 4-100 HP, 440 VOLT AC MOTORS
LASER BEAM GUIDANCE
WASTE DISPOSAL----TRAILING CONVEYOR & TRAIN
MACHINE No.2-SEE OSO TUNNEL MACHINE DATA

*MAXIMUM CAPABILITY

PROGRESS

AVERAGE---55 FT. PER CALENDAR DA
AVERAGE IN SHALE-----------
---153 FT. PER WORKING DA
AVERAGE IN SANDSTONE--------
---72 FT. PER WORKING DA



TUNNEL MACHINE-PROGRESS CHART

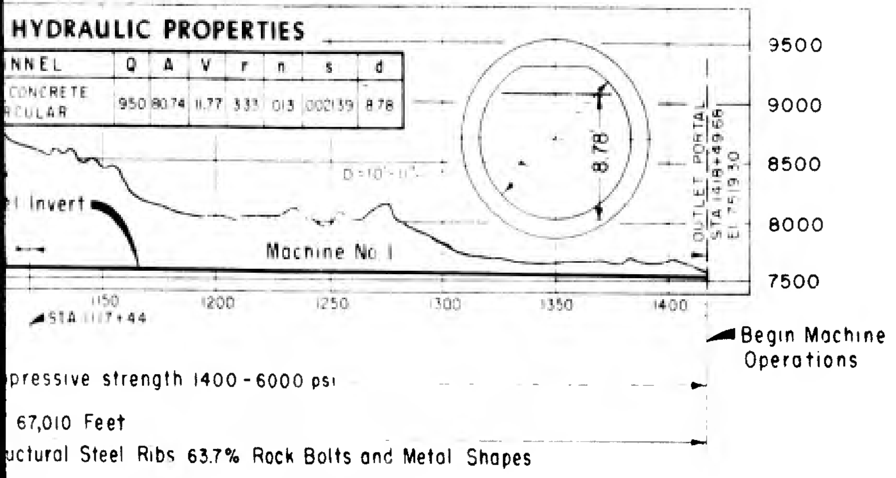
2

AZOTEA TUNNEL

SAN JUAN CHAMA PROJECT

COLORADO - NEW MEXICO

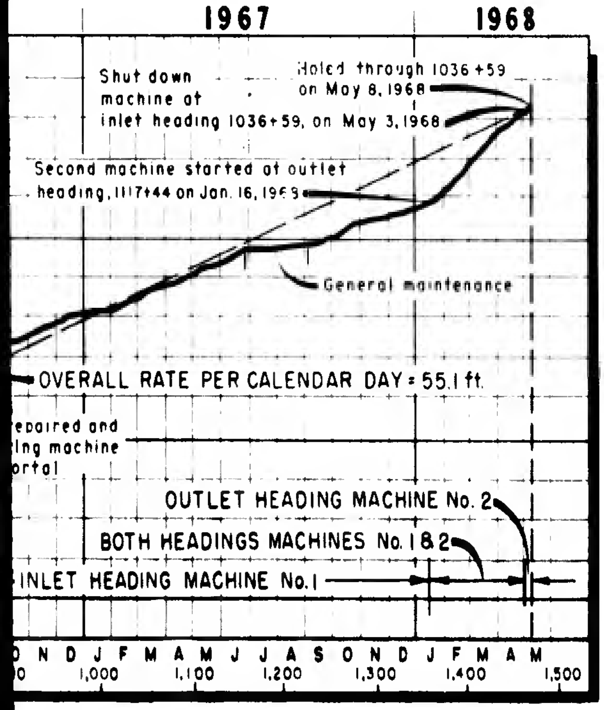
ROFILE



NNEL	Q	A	V	r	n	s	d
CONCRETE RCULAR	950	80.74	11.77	3.33	.013	.002139	8.78

PROGRESS

AVERAGE___55 FT. PER CALENDAR DAY
AVERAGE IN SHALE____________
___153 FT. PER WORKING DAY
AVERAGE IN SANDSTONE_________
___72 FT. PER WORKING DAY



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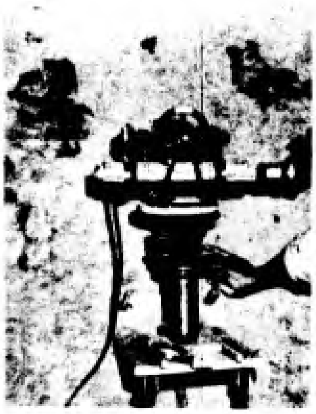
GRESS CHART

CONTRACT DATA

CONTRACTOR-AZOTEA CONTRACTORS JOINT VENTURE; GIBBONS & REED; BOYLES BROS. DRILLING Co; & DUGAN GRAHAM INC.
SPECIFICATION No. DC-6070
BID $13,791,000-INCLUDES APPURTENANT STRUCTURES

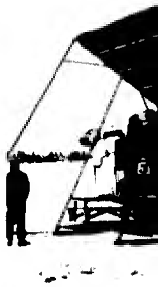
MISCELLANEOUS DATA

TRACK GAGE________30" & 24"
VENTILATION LINE________24"
VOLTAGE SUPPLY INTO TUNNEL__ ___________4,160 VOLTS
No. OF MEN TO OPERATE MACHINE __________5 PER SHIFT
AMBIENT TEMPERATURES AT CUTTER HEAD_________90°-100°F
ROCK TEMPERATURES__65°-78°F



LASER GUN USED FOR GUIDANCE CONTROL

HOLING
TR

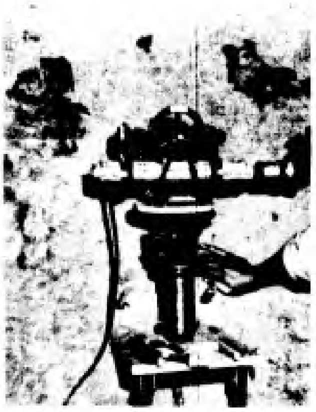


ASSEM

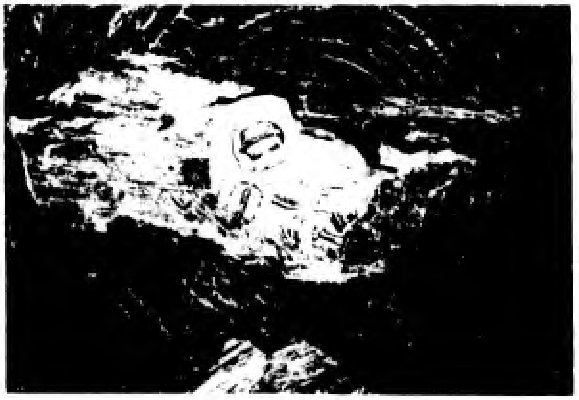
READY FOR LINING

COMPLET

3



LASER GUN USED FOR GUIDANCE CONTROL

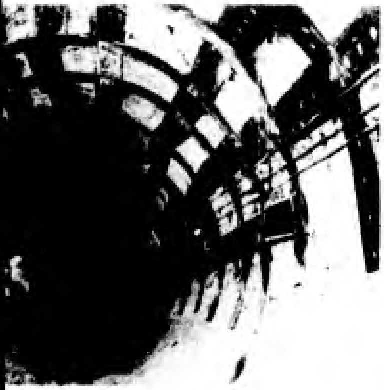


HOLING THROUGH - NOTE CONCENTRIC TRACES OF CUTTER DISCS

MISCELLANEOUS DATA

TRACK GAGE--------30" & 24"
VENTILATION LINE--------24"
VOLTAGE SUPPLY INTO TUNNEL-- -----------4,160 VOLTS
No. OF MEN TO OPERATE MACHINE ----------5 PER SHIFT
AMBIENT TEMPERATURES AT CUTTER HEAD---------90°-100°F
ROCK TEMPERATURES--65°-78°F

ASSEMBLING BORING MACHINE



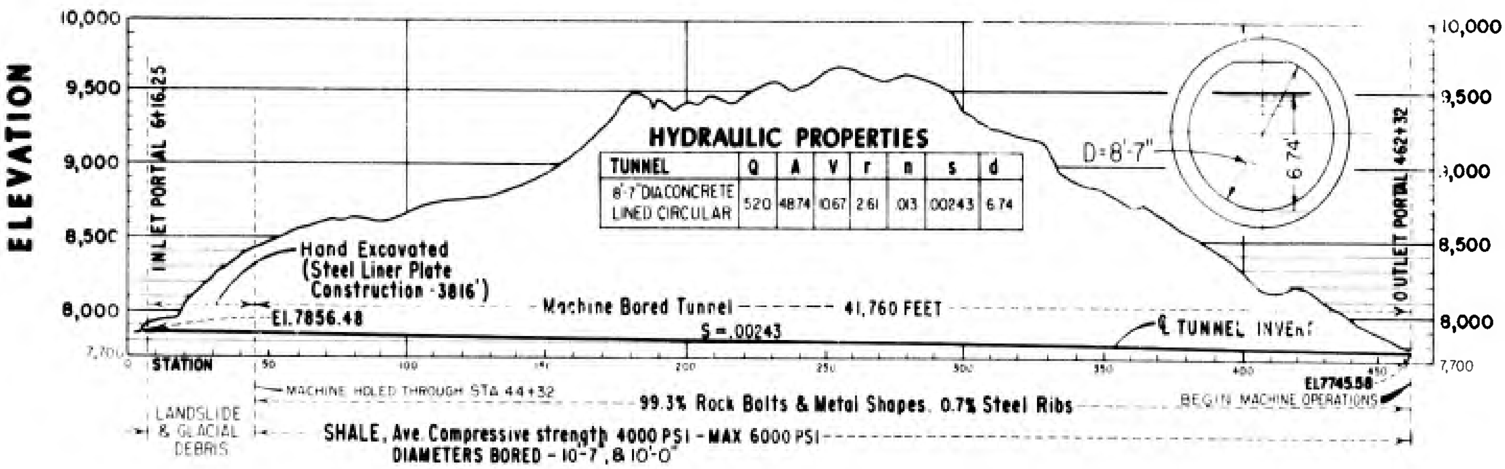
DY FOR LINING

COMPLETED CONCRETE LINED SECTION

BLANCO

SAN JUAN CHAM
COLORADO-NE

TUNNEL PROFILE



HYDRAULIC PROPERTIES

TUNNEL	Q	A	V	r	n	s	d
8'-7" DIA CONCRETE LINED CIRCULAR	520	4874	1067	2.61	.013	.00243	6.74

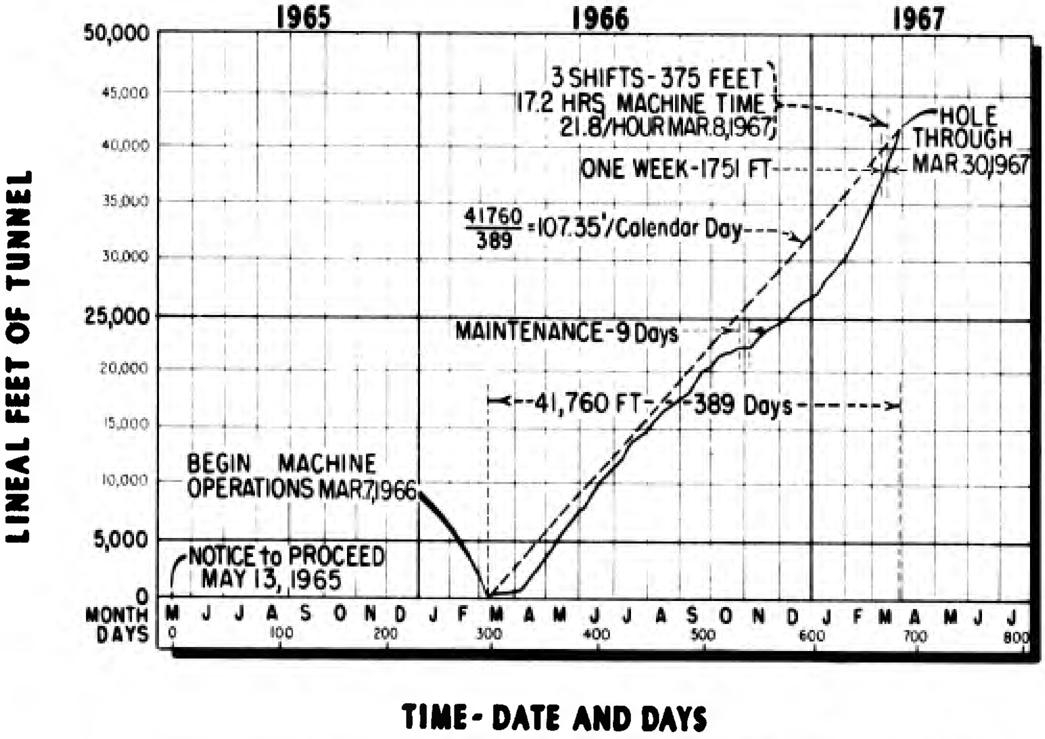
MACHINE DATA

MANUFACTURED BY ROBBINS MODEL 104 - 120
LENGTH............40 FT WEIGHT-120,000 LBS
*THRUST.....372,000 LBS *TORQUE 175,000 FT LBS
CUTTERS....22-11" DISC,
1 TRICONE IN CENTER
HEAD ROTATED BY 4-75 HP; 3 PHASE 440 VOLT MOTORS
LASER BEAM GUIDANCE
WASTE DISPOSAL
TRAILING CONVEYOR & TRAIN

* MAXIMUM CAPABILITY

PROGRESS

AVERAGE....107 FT PER CALENDAR DAY
AVERAGE....154 FT PER WORKING DAY
(14.2 FT/HR)
MAXIMUM....375 FT IN ONE 3 SHIFT DAY
(17.2 HRS MACHINE TIME)
MAXIMUM....21.8 FT PER HOUR



TUNNEL MACHINE-PROGRESS CHART

CONTRACT DATA

COLORADO CONSTRUCTORS
& A.S. HORNER-DENVER, COLO.

SPECIFICATION NO. DC-6261

TOTAL BID FOR 45,576 FEET
OF TUNNEL - $9,188,752.00
(BID ON LINEAR FOOT BASIS)

MISCELLANEOUS DATA

TRACK GAGE__________24"
VENTILATION LINE_____24"
VOLTAGE INTO TUNNEL____
____________4,160 VOLTS
NUMBER OF MEN TO OPERATE
BORING MACHINE________
___________5 PER SHIFT
MAX. AMBIENT TEMPERATURE
AT CUTTERHEAD____110°F
MAX. ROCK TEMPERATURE___
________________93°F

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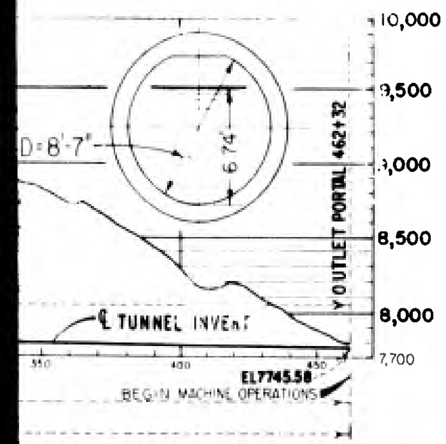
2

BLANCO TUNNEL
SAN JUAN CHAMA PROJECT
COLORADO-NEW MEXICO



ESS

T PER CALENDAR DAY
T PER WORKING DAY
(14.2 FT/HR)
T IN ONE 3 SHIFT DAY
2 HRS MACHINE TIME)
T PER HOUR

CONTRACT DATA

COLORADO CONSTRUCTORS
& A.S. HORNER-DENVER, COLO.

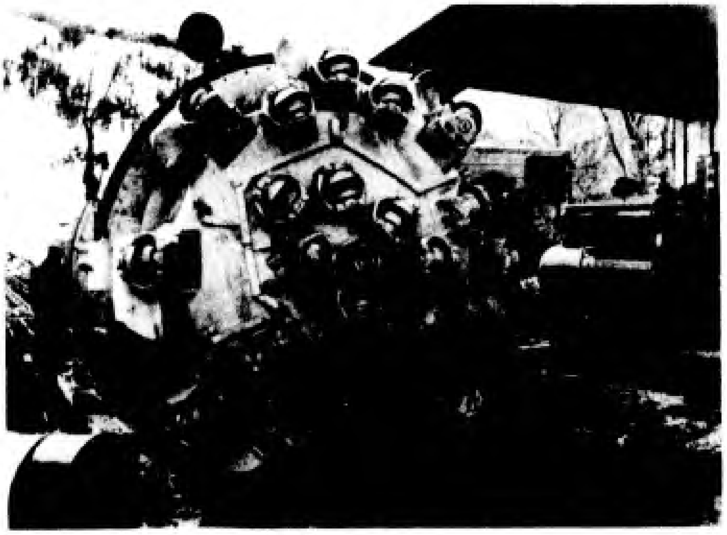
SPECIFICATION NO. DC-6261

TOTAL BID FOR 45,576 FEET
OF TUNNEL - $9,188,752.00
(BID ON LINEAR FOOT BASIS)

MISCELLANEOUS DATA

TRACK GAGE.......... 24"
VENTILATION LINE..... 24"
VOLTAGE INTO TUNNEL....
.... 4,160 VOLTS
NUMBER OF MEN TO OPERATE
BORING MACHINE........
.... 5 PER SHIFT
MAX. AMBIENT TEMPERATURE
AT CUTTERHEAD.... 110°F
MAX. ROCK TEMPERATURE...
.... 93°F

①-OUTLET PORTAL...Surface left by machine supported with rock bolts & steel mat
②-FALLOUT...Area resupported
③-Trailing dust collection & muck conveyor system
④-Left side of machine
⑤-Cutter head



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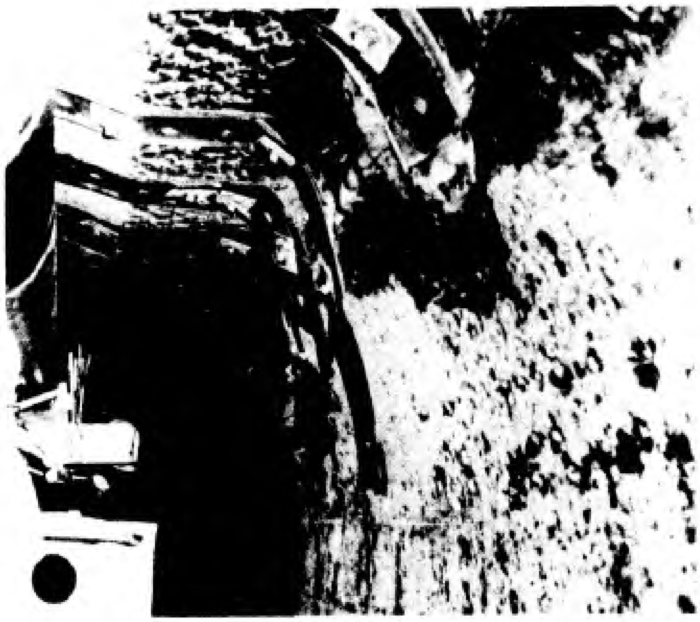
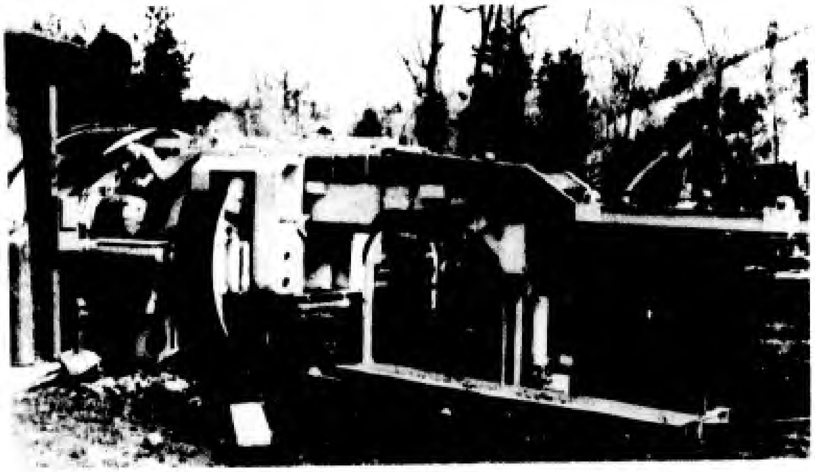
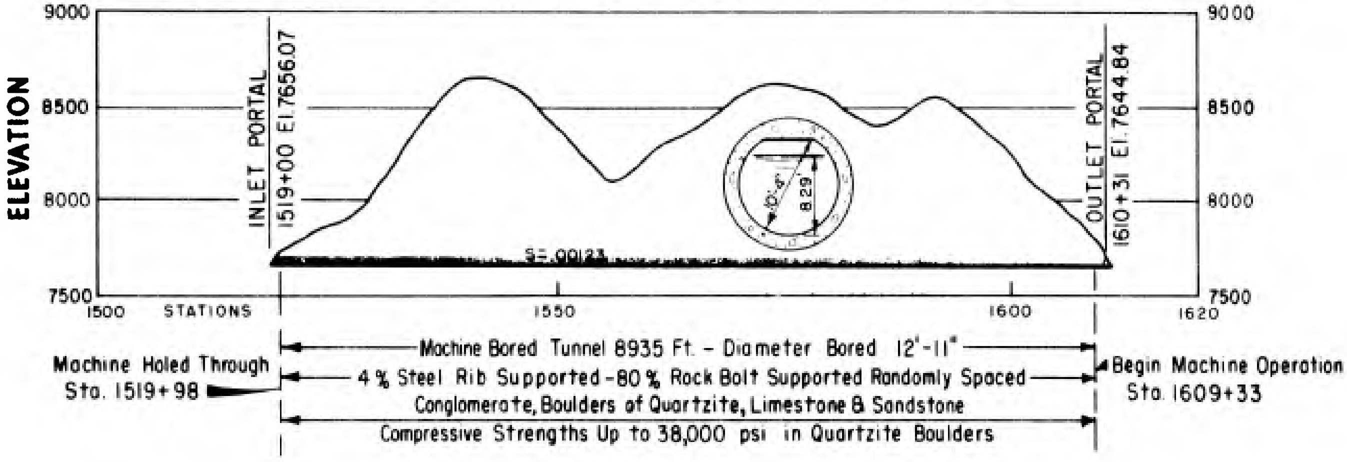




CURRANT T
CENTRAL UTAH P
BONNEVILLE UNIT-

TUNNEL PROFILE

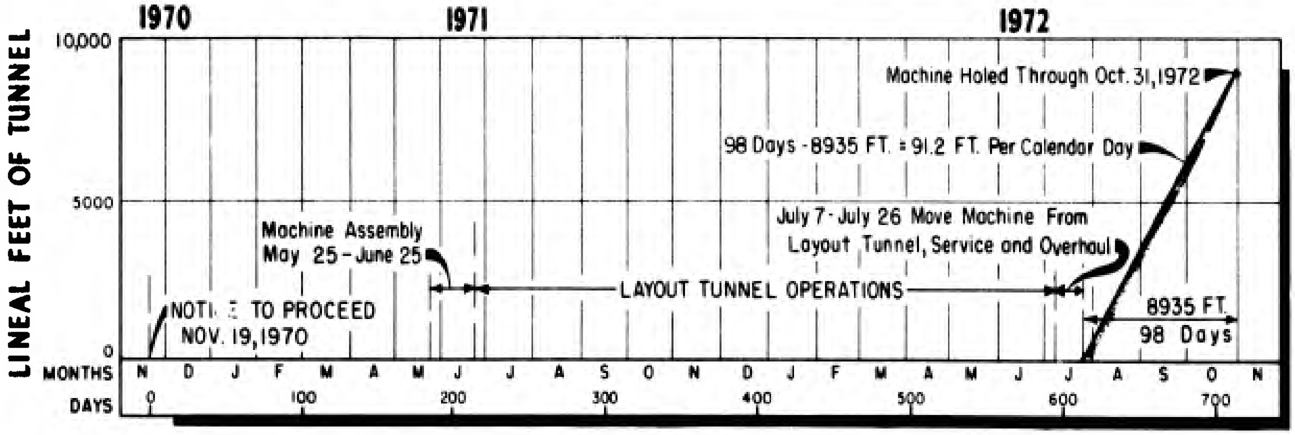


MACHINE DATA

MANUFACTURED BY ROBBINS MODEL 141-127-1
LENGTH_ _ _ _ _ _ _ _45 FT. WEIGHT 200,000 LBS.
THRUST_ _ _ _ _664,000 LBS. TORQUE 630,240 FT. LBS.
CUTTERS_ _ _ _ _ _ _ _ 29 DISC, ONE TRI-DISC AT CENTER
STROKE_ 3.5 FT.
ROTATION_ _ _6-100 HP, 480 VOLT, 3 PHASE ELECTRIC MOTORS
LASER BEAM GUIDANCE SYSTEM
WASTE DISPOSAL_ _ _ _ _ _ _TRAILING CONVEYOR & TRAIN
AVERAGE AVAILABILITY_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _85 %

PROGRESS

MAXIMUM RATE_ _ _ _ _ _ _ _ _ _ _ _
_ _ _ _ _SHIFT 110 FT.
_ _ _ _ _DAY 232 FT.
AVERAGE PER WORKING DAY_ _ _ _ _
_ _ _ _ _ _SHIFT 46 FT.
_ _ _ _ _DAY 133.4 FT.
AVERAGE PER CALENDAR DAY_ _ _ _ _
_ _ _OVERALL 91.2 FT.



TIME-DATE AND DAYS

TUNNEL MACHINE PROGRESS CHART

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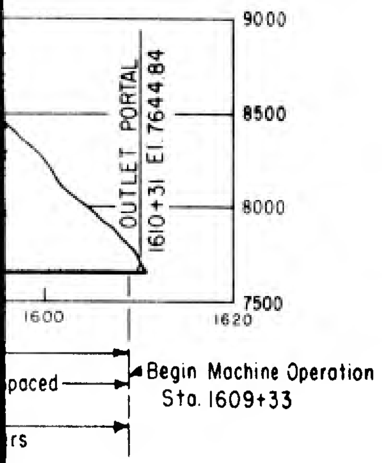
2

URRANT TUNNEL

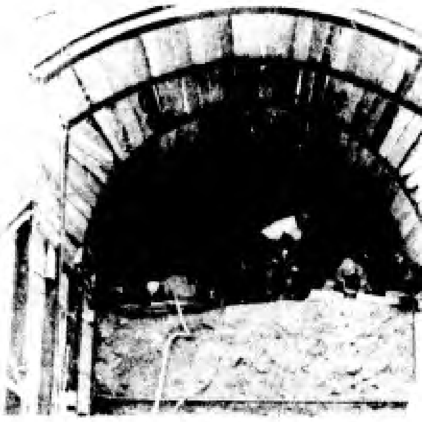
CENTRAL UTAH PROJECT

BONNEVILLE UNIT - UTAH



HYDRAULIC PROPERTIES

TUNNEL	Q	A	V	r	n	s	d
10'-4 DIA. CONCRETE LINED CIRCULAR	620	72.10	8.60	3.14	.013	.00123	8.29



TURNING UNDER AT INLET PO

CONTRACT DATA

CONTRACTOR_ _ _ _ _ S.A. HEALY Co.
SPECIFICATIONS No._ _ _ _ _ DC-6855
BID FOR 9131 FEET OF FINISHED
TUNNEL $3,223,243 ($353 PER FT.)
NOTE: CURRANT & LAYOUT TUNNELS
WERE CONSTRUCTED UNDER
THE SAME CONTRACT.

OGRESS

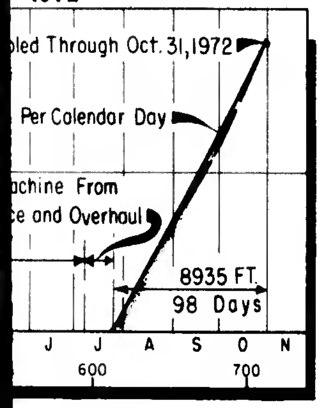
E _ _ _ _ _ _ _ _ _ _ _ _ _
_ _ _ _ _ SHIFT 110 FT.
_ _ _ _ _ DAY 232 FT.
WORKING DAY _ _ _ _ _ _
_ _ _ _ _ _ SHIFT 46 FT.
_ _ _ _ _ DAY 133.4 FT.
CALENDAR DAY _ _ _ _ _
_ _ _ OVERALL 91.2 FT.

MISCELLANEOUS DATA

VENTILATION LINE_ _ _ _ _ _ _ _ _ _36"
VOLTAGE SUPPLY INTO TUNNEL_7200V.
ROCK TEMPERATURE_ _ _ _ _ _ _ _ 55° ±
AMBIENT TEMPERATURE NEAR CUTTER
HEAD_ _ _ _ _ _ _ _ _ _ _ _ _ _65° ±
WATER FLOWS_ _ _ _ SEEPS TO 110 G.P.M.
DUST CONTROL_ _ _ _ WATER SPRAYS AT
CUTTER HEAD MOLE THROAT AND
MATERIAL TRANSFER POINTS
TRACK GAGE_ _ _ _ _ _ _ _ _ _ _ _ _24"

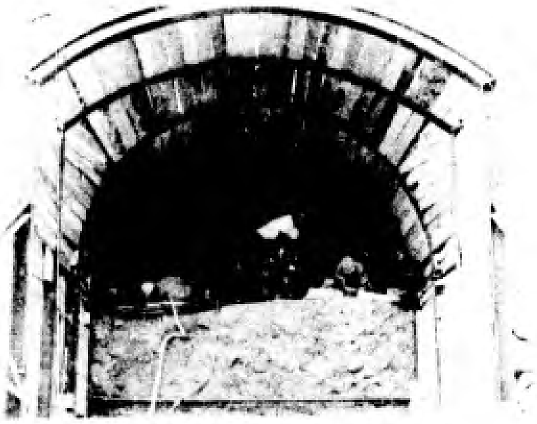
OVERHAULING TUNNELING MACHI
BACKUP EQUIPMENT AT OUTLET

1972



LOADING MUCK CARS AT START OF MACHIN

CHART



TURNING UNDER AT INLET PORTAL

OVERHAULING TUNNELING MACHINE AND BACKUP EQUIPMENT AT OUTLET PORTAL

LOADING MUCK CARS AT START OF MACHINE OPERATIONS

LAYOUT

CENTRAL U

BONNEVIL

CONTRA

CONTRACTOR__

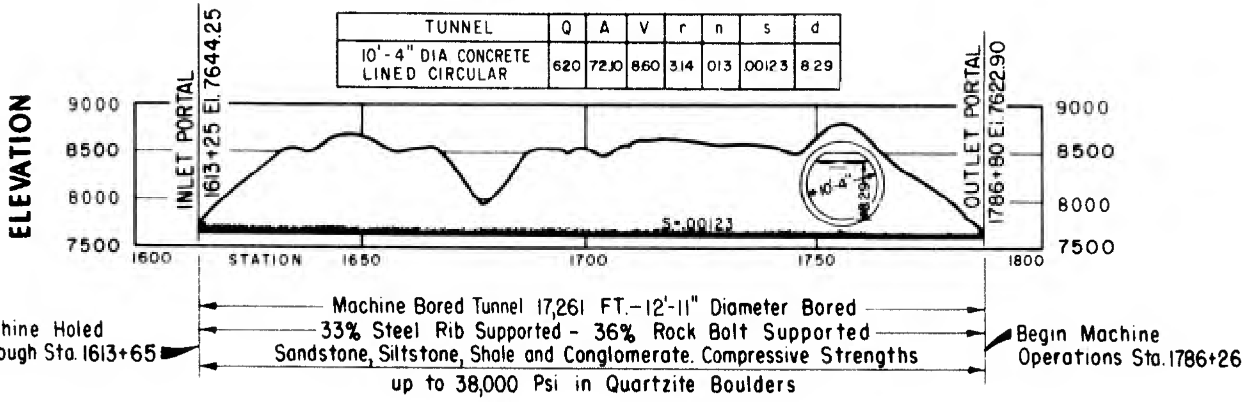
SPECIFICATIONS N

BID FOR 17,355 F

TUNNEL $6,126

HYDRAULIC PROPERTIES

TUNNEL	Q	A	V	r	n	s	d
10'-4" DIA CONCRETE LINED CIRCULAR	620	72.10	8.60	3.14	.013	.00123	8.29



TUNNEL PROFILE

MACHINE DATA

MANUFACTURED BY ROBBINS MODEL 141-127-1

LENGTH_______45 FT. WEIGHT 200,000 LBS.

THRUST 664,000 LBS. TORQUE 630,240 FT. LBS.

CUTTERS______29 DISC, ONE TRI-DISC AT CENTER

ROTATION 6-100 HP, 480 VOLT, 3 PHASE ELECTRIC MOTORS

LASER BEAM GUIDANCE SYSTEM - 3.5 FT. STROKE

BORE DIAMETER 12'-11"

WASTE DISPOSAL________TRAILING CONVEYOR & TRAIN

AVERAGE AVAILABILITY 85 %

PROGRESS

MAXIMUM RATES__________

____SHIFT 92 FT.

____DAY 234 FT.

AVERAGE-PER WORKING DAY___

____SHIFT 40 FT.

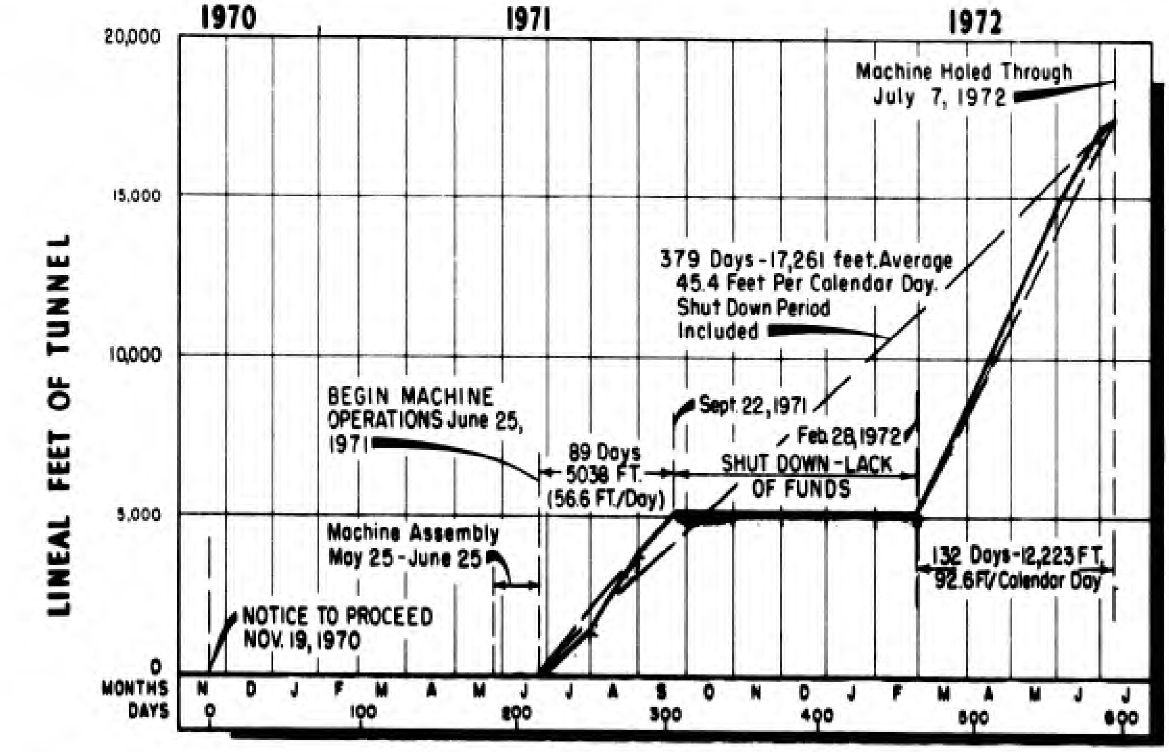
____DAY 114 FT.

AVERAGE-PER CALENDAR DAY___

_OVERALL - 45.4 FT.

_PRIOR TO SHUT DOWN-56.6 FT.

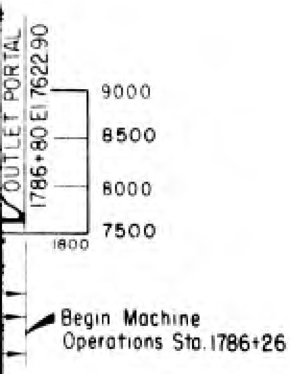
_AFTER SHUT DOWN-92.6 FT.



TIME-DATE AND DAYS

TUNNEL MACHINE-PROGRESS CHART

LAYOUT TUNNEL
CENTRAL UTAH PROJECT
BONNEVILLE UNIT-UTAH



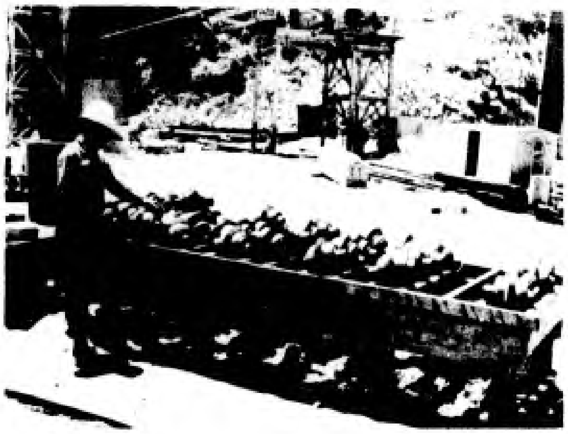
CONTRACT DATA
CONTRACTOR____S.A. HEALY Co.
SPECIFICATIONS No.___DC-6855
BID FOR 17,355 FEET OF FINISHED
TUNNEL $6,126,315 ($353 PER FT.)

MISCELLANEOUS DATA
VENTILATION LINE_________36"
VOLTAGE SUPPLY INTO TUNNEL__
_________7200 VOLTS
ROCK TEMPERATURE____=55°F ±
AMBIENT TEMPERATURE AT CUTTER
HEAD__________=65°F±
WATER FLOWS-SEEPS TO 100 G.P.M.
DUST CONTROL-WATER SPRAYS AT
CUTTER HEAD, MOLE
THROAT AND MATERIAL
TRANSFER POINTS
THIS MACHINE USED IN CURRANT
TUNNEL NEARBY
TRACK GAGE___________24"

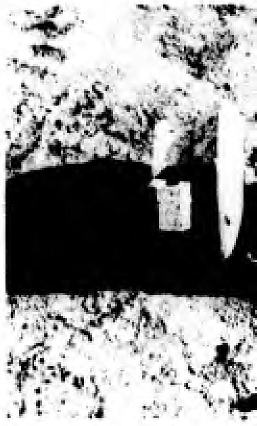
MACHINE ASSEMBLY

RESS

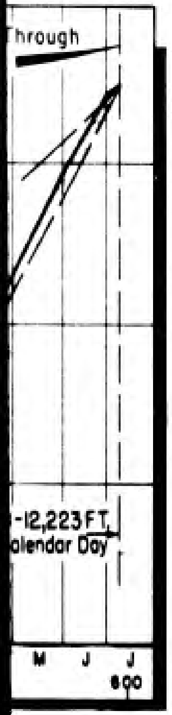
__SHIFT 92 FT.
__DAY 23.1 FT.
ORKING DAY___
__SHIFT 40 FT.
__DAY 114 FT.
LENDAR DAY___
45.4 FT.
UT DOWN-56.6 FT.
T DOWN-92.6 FT.

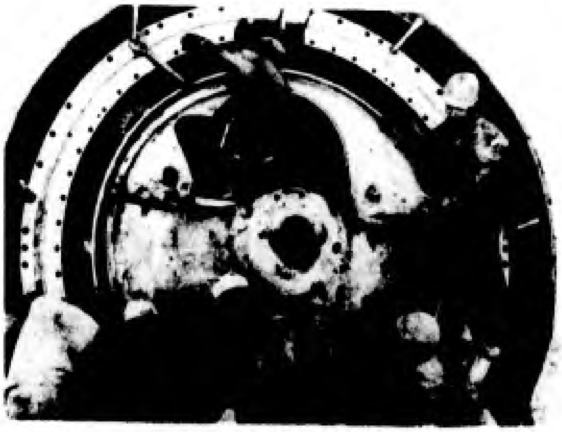


RACK OF REBUILT DISC CUTTERS

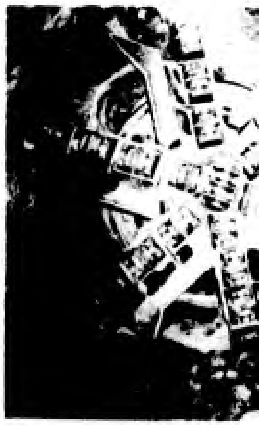


WORN TRI-DI





REPLACING MAIN BEARING



CUTTER HEAD

HART

3

A
36"

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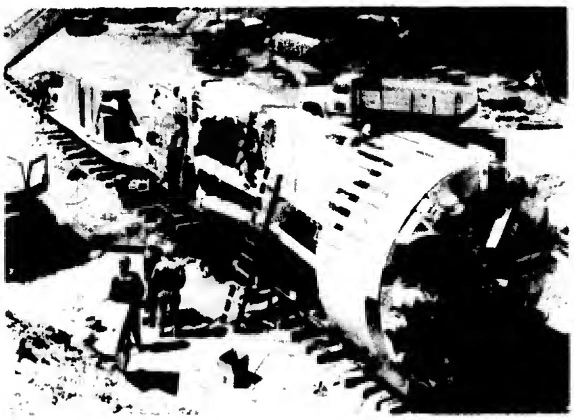
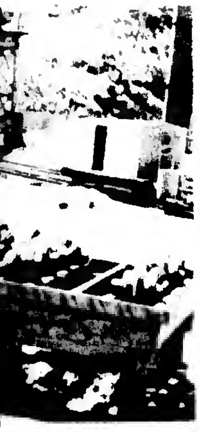
°F±
P.M.
AT

NT

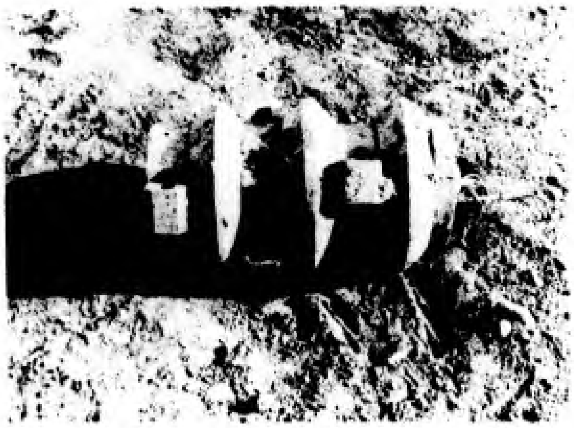
24"



MACHINE ASSEMBLY



C CUTTERS



WORN TRI-DISC CENTER CUTTER

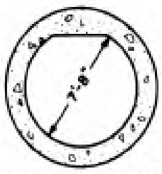
EARING

CUTTER HEAD AT HOLE THROUGH

NAST T

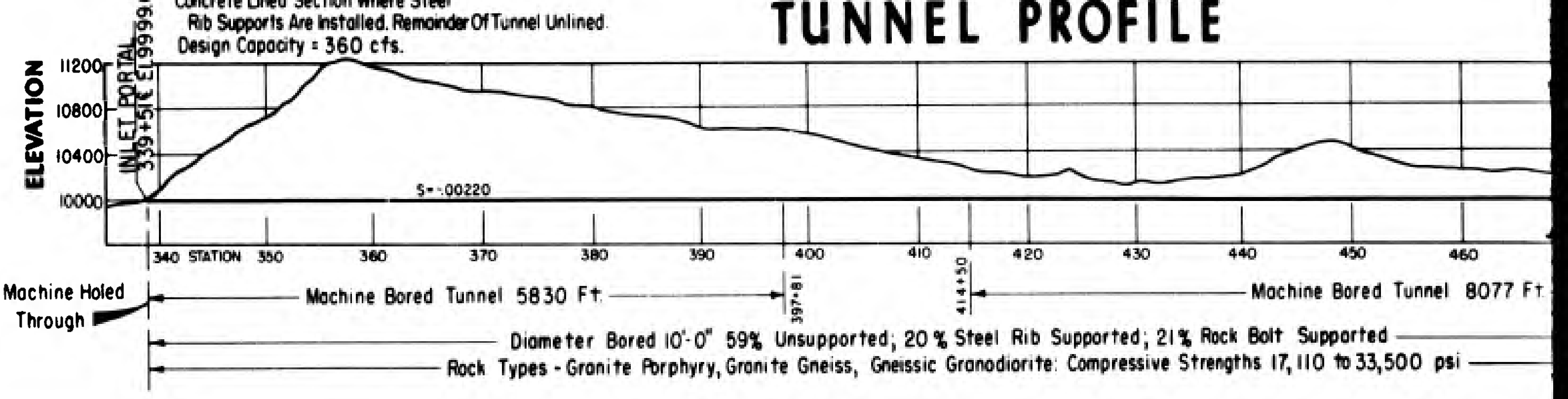
FRYINGPAN - ARKAN

COLORA



Concrete Lined Section Where Steel Rib Supports Are Installed. Remainder Of Tunnel Unlined.
Design Capacity = 360 cfs.

TUNNEL PROFILE



MACHINE DATA

MANUFACTURED BY WIRTH & COMPANY, ERKELENZ, GERMANY MODEL_TB II-300 H
LENGTH___25FT. WITH 90FT. TRAILING POWER SUPPORT UNIT WEIGHT, INCLUDING TRAILING CONVEYOR___120 TONS
MAX. THRUST_________________873,000 LBS. MAX. TORQUE____________445,000 FT. LBS.
CUTTER HEAD__ORIGINAL HEAD HAD 3' DIA. WITH FLAT FACE, REMAINDER SLOPED BACK 19°-26 BUTTON INSERT CUTTERS__________NO FACE OR ARCH SHIELDS. CUTTER HEAD LATER REPLACED WITH FLAT FACED HEAD, 29 CUTTERS, WITH FACE & ARCH SHIELDS.
ROTATION, THRUST & GRIPPERS HYDRAULICALLY OPERATED.
LASER BEAM GUIDANCE
WASTE DISPOSAL______TRAILING CONVEYOR & TRAIN

PR

MAXIMUM FOR 1

AVERAGE PER W

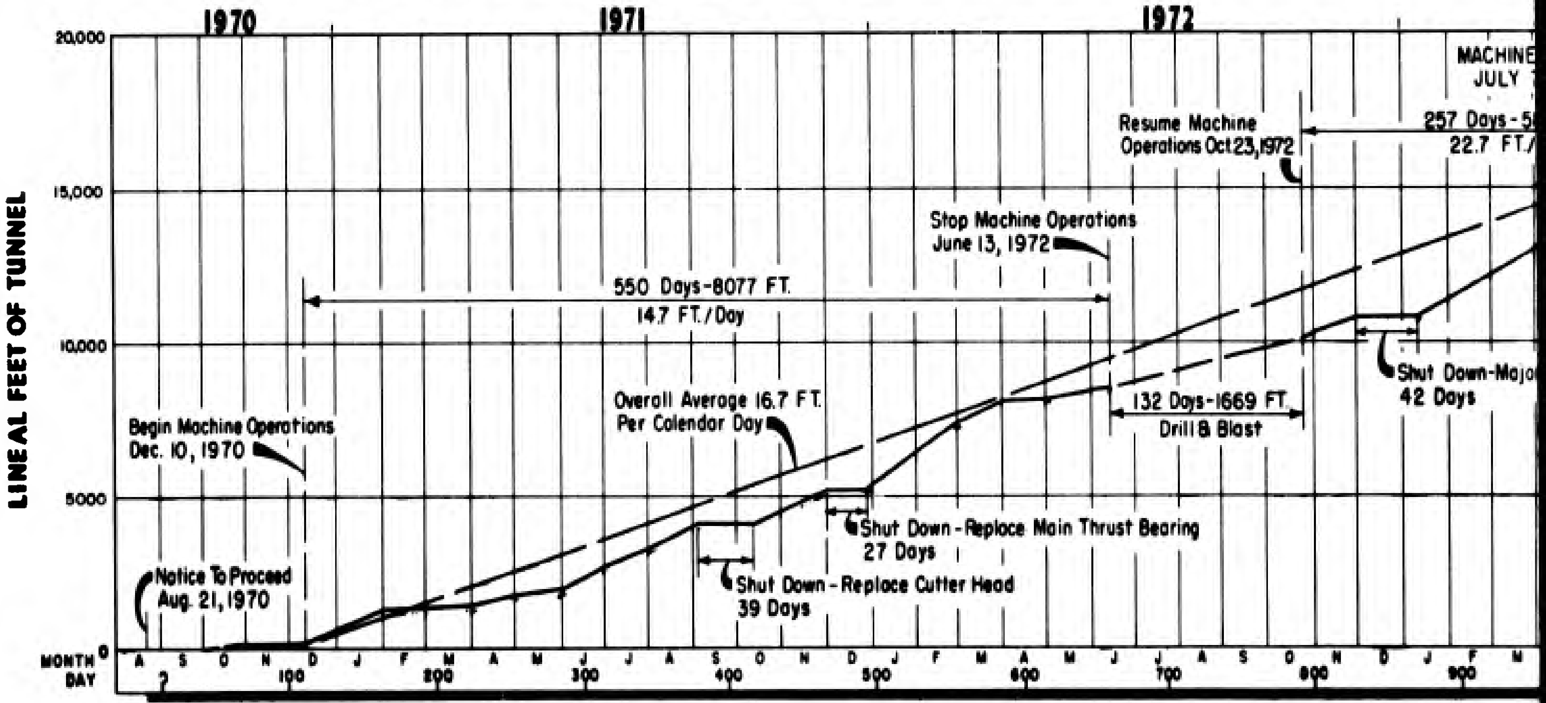
PER

MISCELLA

TRACK GAGE ____
VENTILATION LINE
VOLTAGE SUPPLY INT
TYPICAL UNDERGROU
CREW_____
MACHINE LIMITED T
3 SHIFT DAY - 6 DA

CONTRACT DATA

CONTRACTOR__________PETER KIEWIT SONS Co.
SPECIFICATIONS No.____________DC-6829
BID (TUNNEL PORTION)________$ 6,828,754



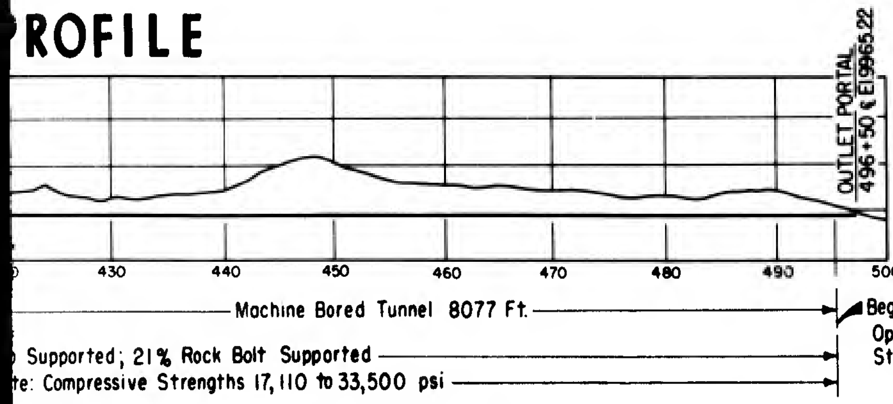
TIME-DATE AND DAYS

TUNNEL MACHINE-PROGRESS CHART

2

NAST TUNNEL
FRYINGPAN - ARKANSAS PROJECT
COLORADO

ROFILE



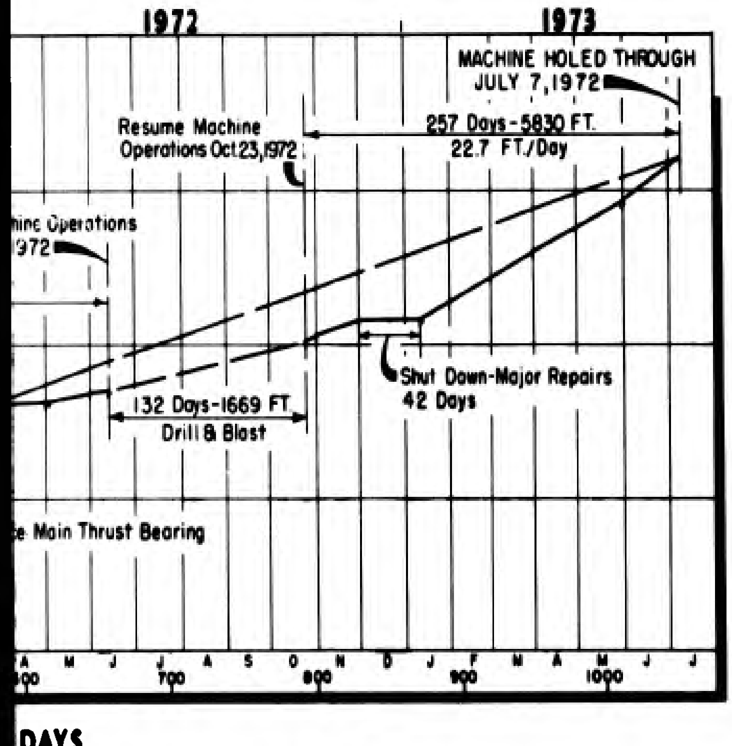
L_TB II-300 H
OR___120 TONS
45,000 FT. LBS.
TON INSERT
FLAT FACED HEAD,

PROGRESS

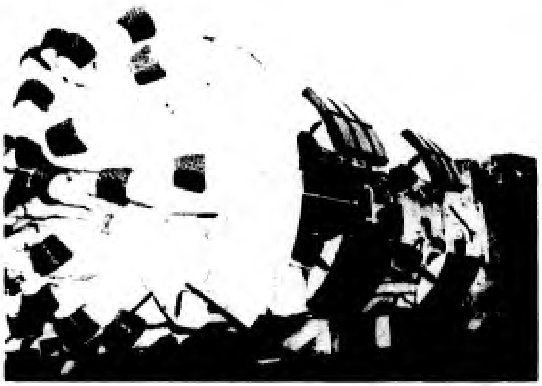
MAXIMUM FOR 1 DAY_________73 FT.
1 SHIFT______33 FT.
AVERAGE PER WORKING DAY___17.4 FT.
PER SHIFT_____5.8 FT.
PER CALENDAR DAY_16.7 FT.

MISCELLANEOUS DATA

TRACK GAGE_________________36"
VENTILATION LINE______________22"
VOLTAGE SUPPLY INTO TUNNEL___4160 VOLTS
TYPICAL UNDERGROUND MACHINE CREW_______________11 MEN
MACHINE LIMITED TO 580 FT. RADIUS CURVE
3 SHIFT DAY - 6 DAY WEEK OPERATION



OGRESS CHART



WIRTH TUNNEL BORING MACHINE ON RAIL FLAT CAR

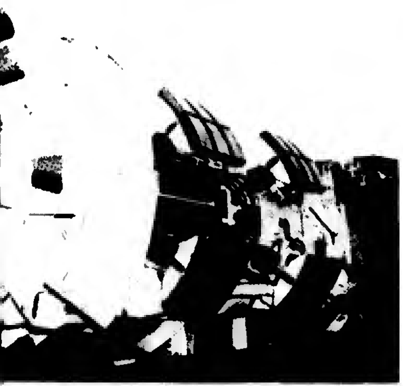
TRANSITION FROM
EXCAVATION (DRI
EXCAVATION AT S
PORTAL

LOOKING UPSTREAM TOWARD HEADING SHOWING 40' BRIDGE SECTION OF MUCK CONVEYOR. THIS PROVIDES SPACE IN WHICH TRACK IS LAYED

VIEW LOOKING DOWN STREAM FROM STA.480+00 SHOWING EXCAVATED SURFACE AND CURVE

VIEW UPSTREAM AT POINT O
BORING STA.397+79

3

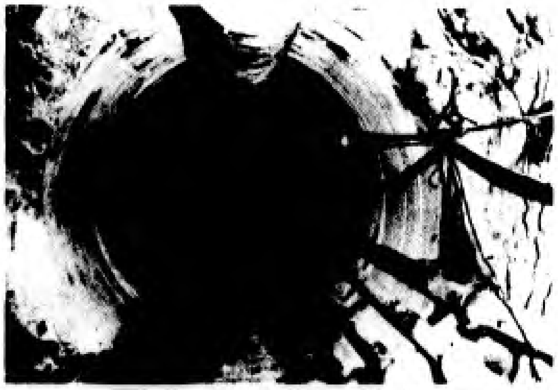


EL BORING MACHINE ON RAIL FLAT CAR

TRANSITION FROM CONVENTIONAL EXCAVATION (DRILL & BLAST) TO MACHINE EXCAVATION AT STA. 495+27 NEAR OUTLET PORTAL

LOOKING UPSTREAM TOWARD HEADING SHOWING 40' BRIDGE SECTION OF MUCK CONVEYOR. THIS PROVIDES SPACE IN WHICH TRACK IS LAYED

EAM FROM STA 490+00
ACE AND CURVE

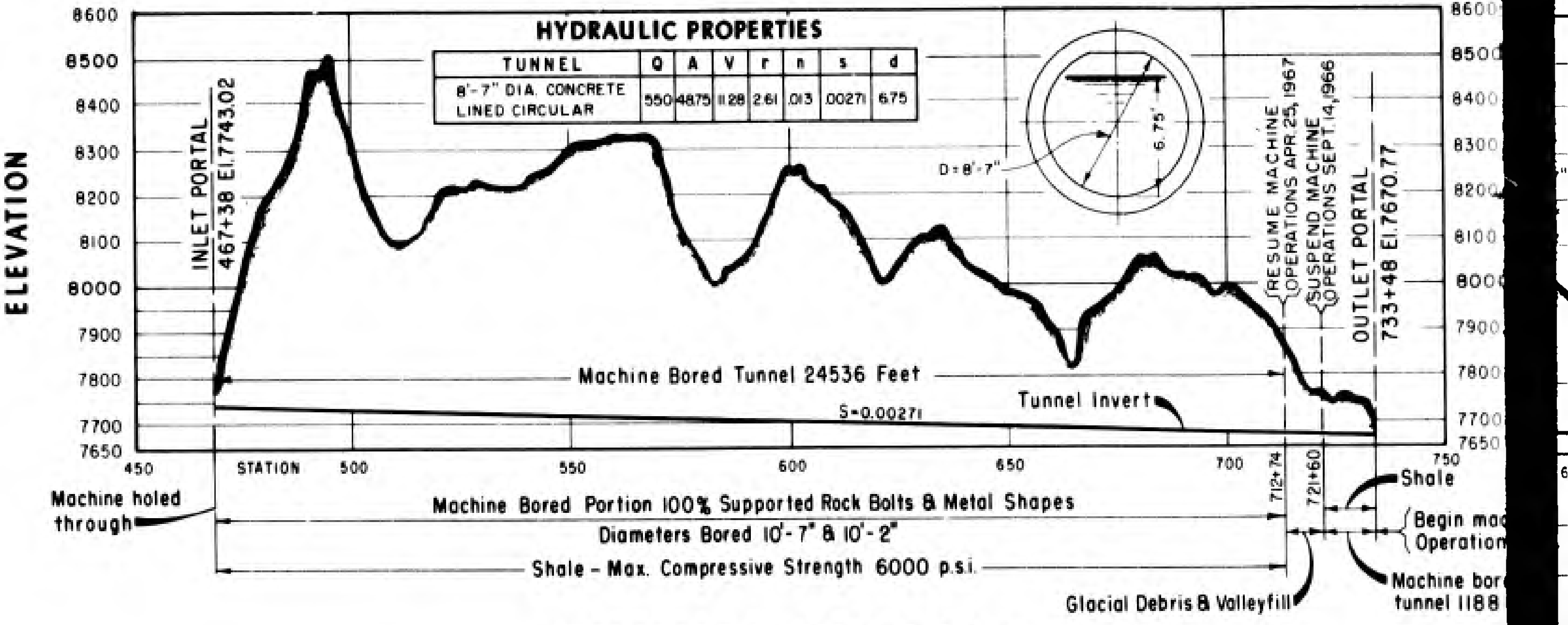


VIEW UPSTREAM AT POINT OF RENEWED MACHINE BORING STA. 397+79

OSO T

SAN JUAN CH

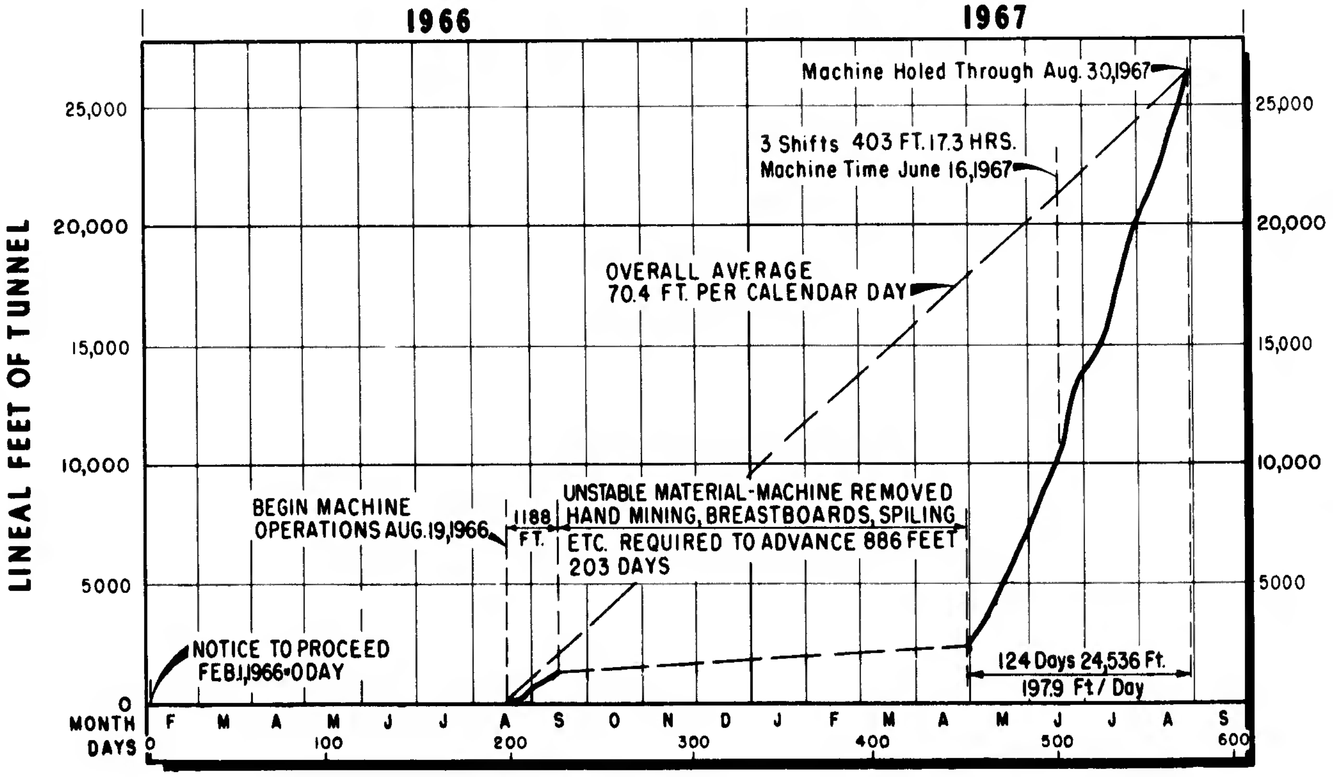
COLORADO



HYDRAULIC PROPERTIES

TUNNEL	Q	A	V	r	n	s	d
8'-7" DIA. CONCRETE LINED CIRCULAR	550	48.75	11.28	2.61	.013	.00271	6.75

TUNNEL PROFILE



TIME-DATE AND DAYS

TUNNEL MACHINE-PROGRESS CHART

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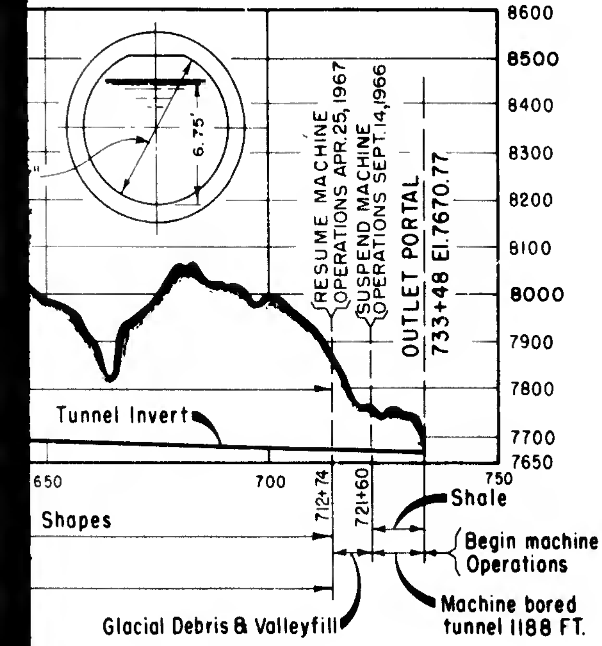
OSO TUNNEL
SAN JUAN CHAMA PROJECT
COLORADO - NEW MEXICO



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MACHINE DATA

MANUFACTURED BY ROBBINS MODEL 104-121A
LENGTH________40 FT. WEIGHT 105,000 LBS.
*THRUST___372,000 LBS. *TORQUE 175,000 FT. LBS.
CUTTERS_____22 DISC, 1 - TRICONE IN CENTER
ROTATION BY 4-75 HP ELECTRIC MOTORS 440 V.
LASER BEAM GUIDANCE
WASTE DISPOSAL___TRAILING CONVEYOR & TRAIN

*MAXIMUM CAPABILITY

PROGRESS

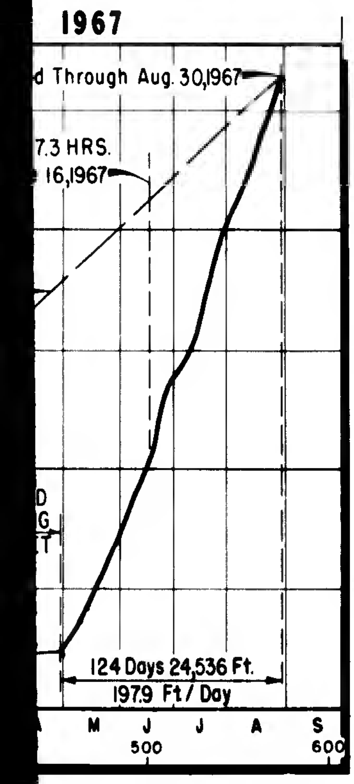
AVERAGE (OVERALL)_____________
_______70.4 FT. PER CALENDAR DAY
AVERAGE (EXCLUDING TIME IN BAD GROUND)_
_______197.9 FT. PER CALENDAR DAY
MAXIMUM (17.3 HRS. MACHINE TIME)______
_______403 FT. IN ONE 3 SHIFT DAY

CONTRACT DATA

CONTRACTOR-BOYLES BROS. DRILLING Co.
SPECIFICATION No. DC-6380
BID (TUNNEL PORTION) $ 5,301,816

MISCELLANEOUS DATA

TRACK GAGE_____________24"
VENTILATION LINE_________24"
VOLTAGE SUPPLY INTO TUNNEL____
______________4,160 VOLTS
No OF MEN TO OPERATE MACHINE
______________5 PER SHIFT
AMBIENT TEMPERATURES AT CUTTER HEAD_______________90° F
ROCK TEMPERATURE______74° F
AFTER COMPLETING THE EXCAVATION IN OSO TUNNEL THIS MACHINE WAS REBUILT AND HEAD ENLARGED TO 12'-8" DIA. THEN PUT IN OUTLET END OF AZOTEA TUNNEL



S CHART

MUCK TRAIN AT DISPOSAL AREA

OUT

NOTE CHANNEL S
REQUIRED IN

WASTE HA
AND LO

DEL 104-121A
05,000 LBS.
,000 FT. LBS.
E IN CENTER
TORS 440 V.

YOR & TRAIN

NDAR DAY
GROUND)-
NDAR DAY
E)------
HIFT DAY

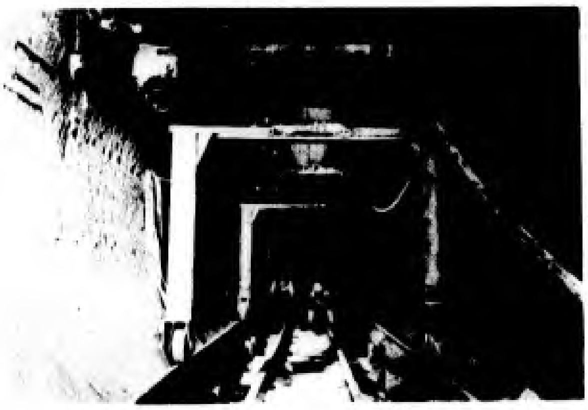
NEOUS DATA

-------------24"
NE---------24"
INTO TUNNEL----
----4,160 VOLTS
PERATE MACHINE
----5 PER SHIFT
RATURES AT CUTTER
----------90° F
TURE------74° F
NG THE EXCAVATION
THIS MACHINE WAS
EAD ENLARGED TO
PUT IN OUTLET END
NNEL

EA

OUTLET PORTAL

NOTE CHANNEL SPILING AND BREAST BOARDS REQUIRED IN UNSTABLE MATERIAL



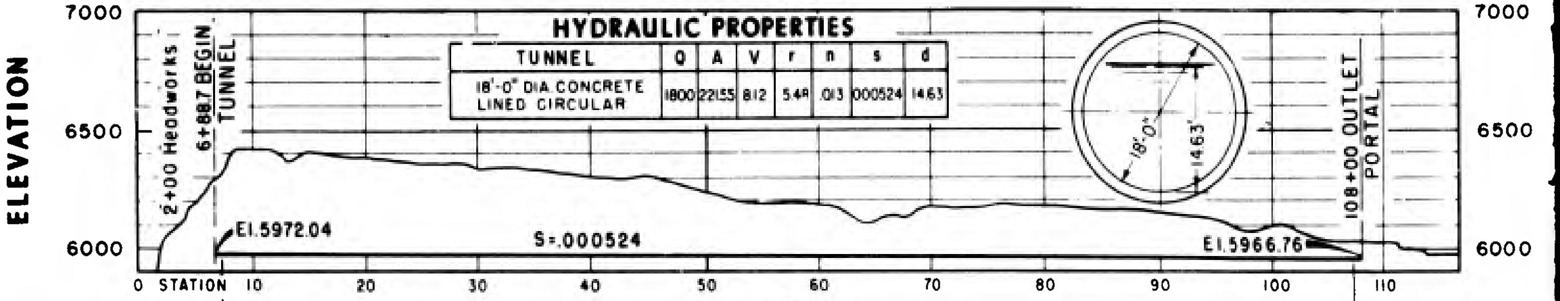
WASTE HANDLING CONVEYOR AND LOADING SYSTEMS

TUNN

NAVAJO INDIAN I

NEW

TUNNEL PROFILE



HYDRAULIC PROPERTIES

TUNNEL	Q	A	V	r	n	s	d
18'-0" DIA. CONCRETE LINED CIRCULAR	1800	221.55	8.12	5.49	.013	.000524	14.63

STA. 7+45 Machine Holed Through — Machine Bored Tunnel 9979 FT. — STA. 107+24 Begin Machine Operations

Diameters Bored 19'-10" and 20'-10" 57% Unsupported; 39% Light Rib Support; 4% Rock Bolt

Sandstone 4000 to 6000 psi. Compressive Strength and Minor amounts of Shale

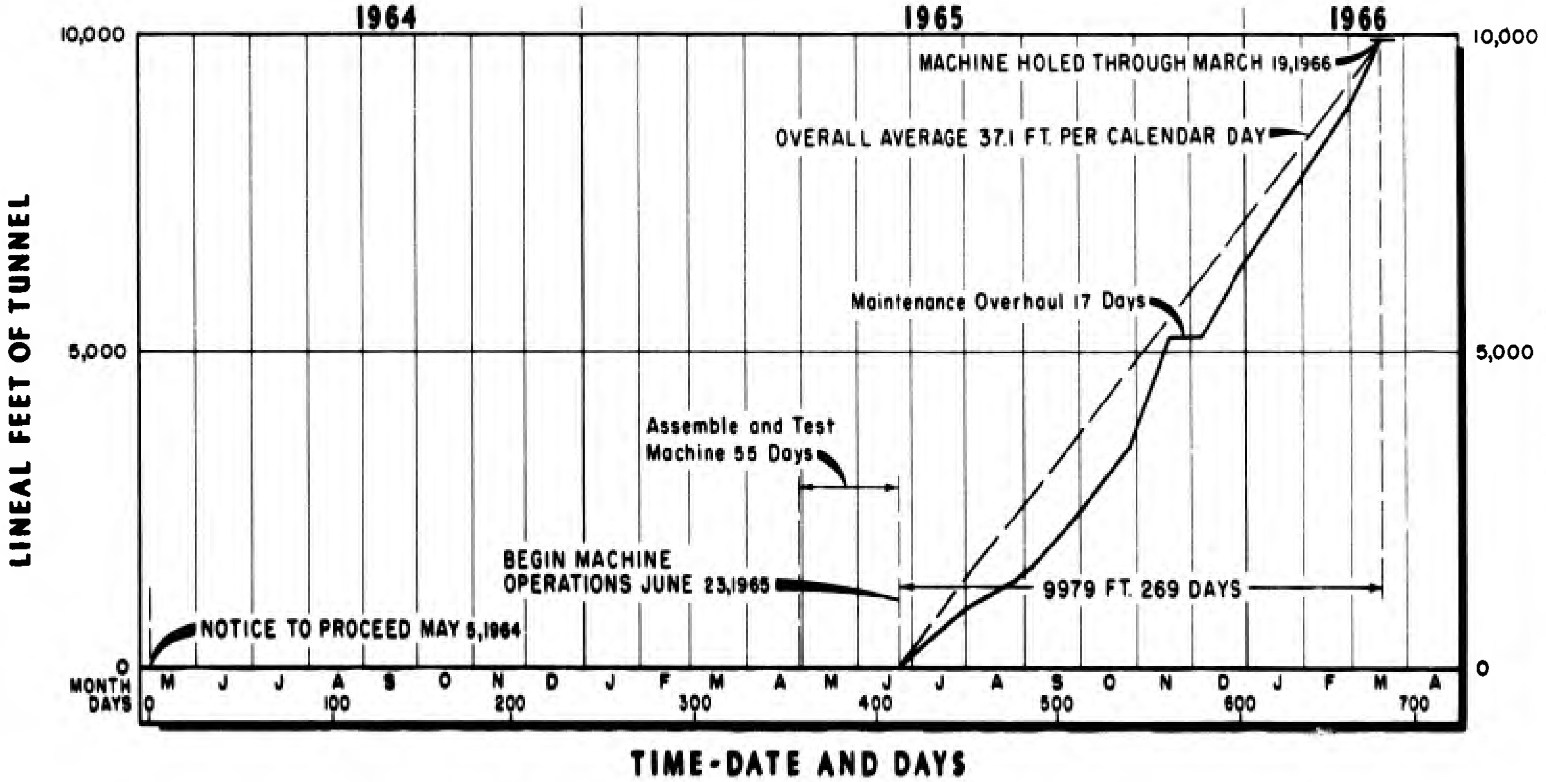
MACHINE DATA

MANUFACTURED BY HUGH B. WILLIAMS MFG. Co.
(A SUBSIDIARY OF HUGHES TOOL Co.) MODEL BETTI I
LENGTH______64 FT. WEIGHT 560,000 LBS.
*THRUST________________1,400,000 LBS.
CUTTERS-43 ROLLING TEETH & ROLLING DISCS
HEAD ROTATED BY 5-200 HP, 2300 V. ELECTRIC MOTORS
LASER BEAM GUIDANCE
WASTE DISPOSAL____TRAILING CONVEYOR & TRAIN

*MAXIMUM CAPABILITY

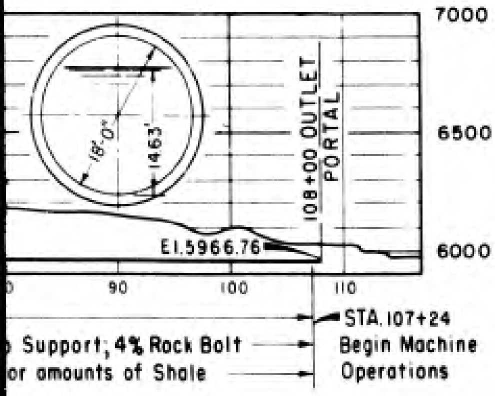
PROGRESS

MAX. FOR ONE DAY_________160 FT.
UNSUPPORTED & 97 FT. IN A
SUPPORTED SECTION
AVERAGE____________________
__37.1 FT. PER CALENDAR DAY
__51.5 FT. PER WORKING DAY



TUNNEL MACHINE-PROGRESS CHART

TUNNEL NO. I
NAVAJO INDIAN IRRIGATION PROJECT
NEW MEXICO



PROGRESS

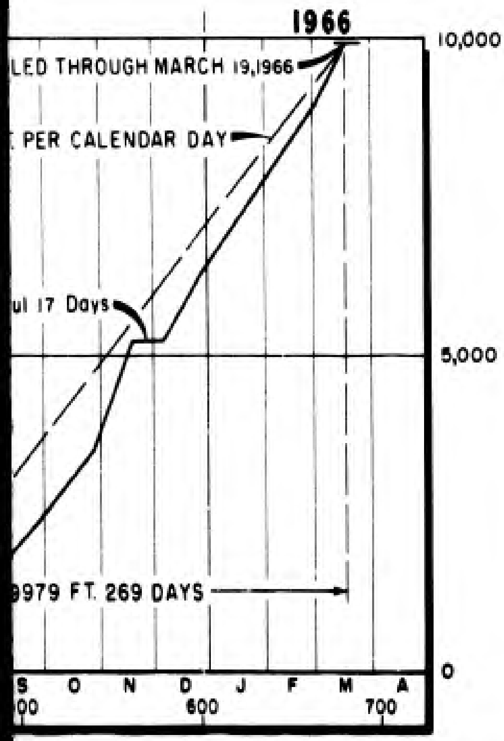
R ONE DAY_________160 FT.
UNSUPPORTED & 97 FT. IN A
SUPPORTED SECTION
E____________________
__37.1 FT. PER CALENDAR DAY
__51.5 FT. PER WORKING DAY

CONTRACT DATA

CONTRACTOR-FENIX & SCISSON INC.
SPECIFICATION No. DC-6077
BID-$ 324.50 PER LINEAR FOOT
TOTAL COST TO CONSTRUCT
TUNNEL $ 3,257,980

MISCELLANEOUS DATA

TRACK GAGE___________36"
VENTILATION LINE_______42"
POWER SUPPLY INTO TUNNEL__ ___________2300 VOLTS
AMBIENT TEMPERATURE AT CUTTER HEAD_________ABOUT 70°F
ROCK TEMPERATURE_ABOUT 65°F
STRUCTURAL STEEL RIB SUPPORT USED WAS HALF CIRCLE 4" I PINNED AT OR NEAR SPRINGLINE



S CHART

PORTION OF MACHINE ARRIVING AT JOB SITE FROM DALLAS TEXAS

ASSEMBLING MACHINE NEAR TUNNEL PORTAL

RESULT OF PINNING SUPPORTS IN SHALE

FIN

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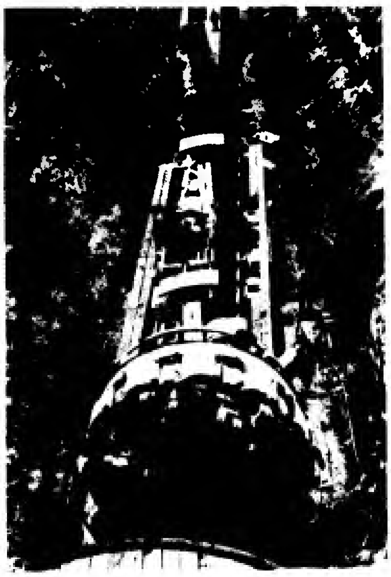
PORTION OF MACHINE ARRIVING AT JOB SITE FROM DALLAS TEXAS


ASSEMBLING MACHINE NEAR TUNNEL PORTAL


RESULT OF PINNING SUPPORTS IN SHALE


FINAL ADJUSTMENT PRIOR TO ENTERING PORTAL

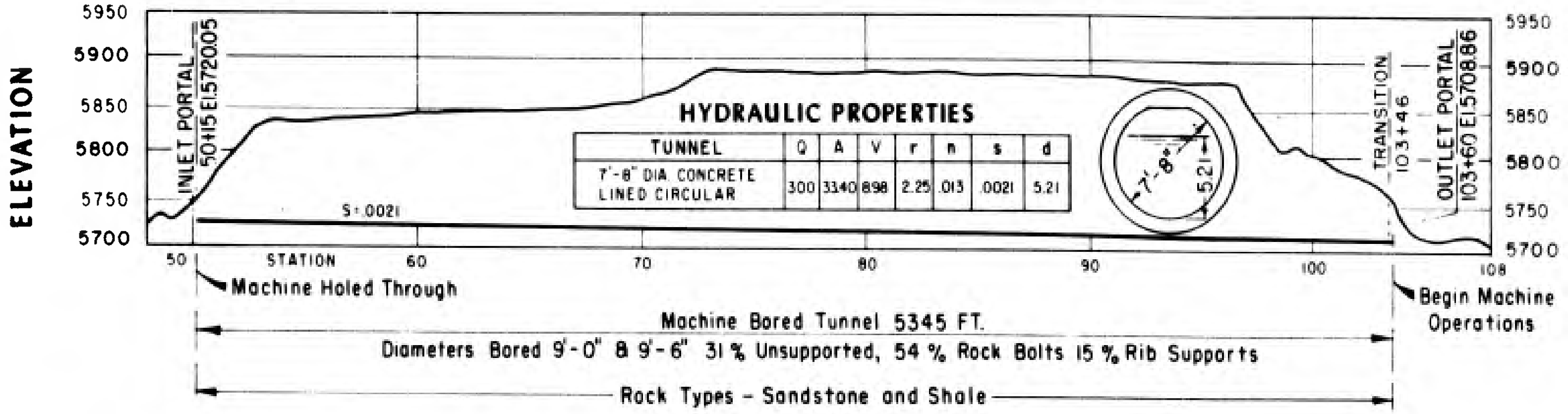

CAR IN LOADING POSITION NOTE HALF CIRCLE SUPPORTS PINNED AT SPRINGLINE IN SANDSTONE

STARVATIO

CENTRAL UT

BONNEVILLE

TUNNEL PROFILE



HYDRAULIC PROPERTIES

TUNNEL	Q	A	V	r	n	s	d
7'-8" DIA. CONCRETE LINED CIRCULAR	300	3340	898	2.25	.013	.0021	5.21

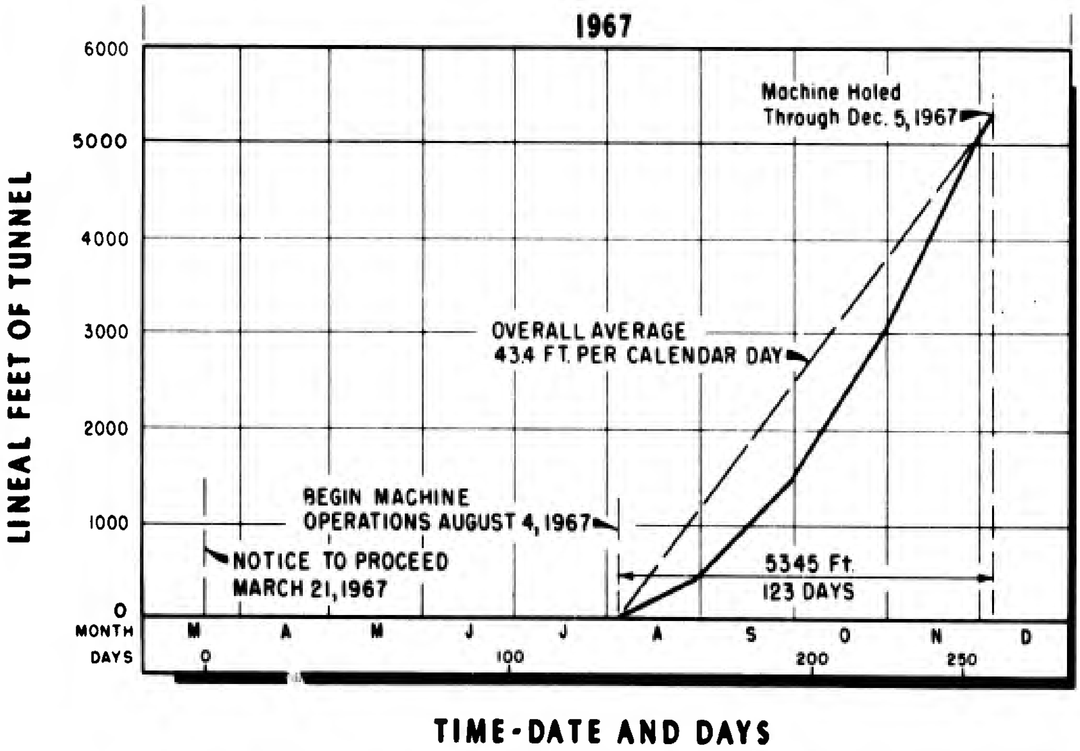
MACHINE DATA

MANUFACTURED BY ROBBINS MODEL 81-113
LENGTH--------48 FT. WEIGHT 66,000 LBS.
*THRUST--- 220,000 LBS.
CUTTERS-----------1-TRICONE AND 20 DISC
HEAD ROTATED BY 2-100 HP, 440 VOLT MOTORS
LASER BEAM GUIDANCE
WASTE DISPOSAL---TRAILING CONVEYOR & TRAIN

* MAXIMUM CAPABILITY

PROGRESS

MAXIMUM FOR I DAY--128 FT. (2 SHIFTS)
FOR I SHIFT---------66 FT.
AVERAGE PER DAY--64.4 FT.(2 SHIFTS)
PER SHIFT--------32.2 FT.
PER CALENDAR DAY---43.4 FT.



TUNNEL MACHINE-PROGRESS CHART

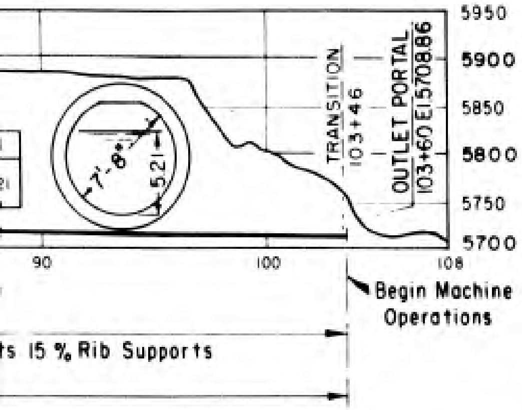
CONTRACT DAT

CONTRACTOR W.W. CLYDE
SPECIFICATION No. DC-
BID (TUNNEL PORTION) $8

MISCELLANEOUS D

TRACK GAGE----------
VENTILATION LINE------
VOLTAGE SUPPLY INTO TUN
-----------4,160
No. OF MEN TO OPERATE MA
-----------4 PER
MACHINE OPERATED 2-8
SHIFTS PER DAY. 3 rd
FOR MAINTENANCE
AMBIENT TEMPERATURE AT
HEAD-----------
ROCK TEMPERATURE----

STARVATION TUNNEL
CENTRAL UTAH PROJECT
BONNEVILLE UNIT - UTAH



PROGRESS

FOR I DAY__128 FT. (2 SHIFTS)
R I SHIFT_________66 FT.
PER DAY__64.4 FT.(2 SHIFTS)
R SHIFT________32.2 FT.
R CALENDAR DAY___43.4 FT.

CONTRACT DATA

CONTRACTOR W.W. CLYDE & Co.
SPECIFICATION No. DC-6489
BID (TUNNEL PORTION) $870,065

MISCELLANEOUS DATA

TRACK GAGE____________24"
VENTILATION LINE________24"
VOLTAGE SUPPLY INTO TUNNEL__ ____________4,160 VOLTS
No. OF MEN TO OPERATE MACHINE ___________4 PER SHIFT
MACHINE OPERATED 2-8 HOUR SHIFTS PER DAY. 3 rd SHIFT FOR MAINTENANCE
AMBIENT TEMPERATURE AT CUTTER HEAD____________70° F
ROCK TEMPERATURE_____58° F

PARTIALLY ASSEMBLED MACHINE AT PORTAL. NOTE SPECIALLY CONSTRUCTED CONCRETE "LAUNCH PAD"

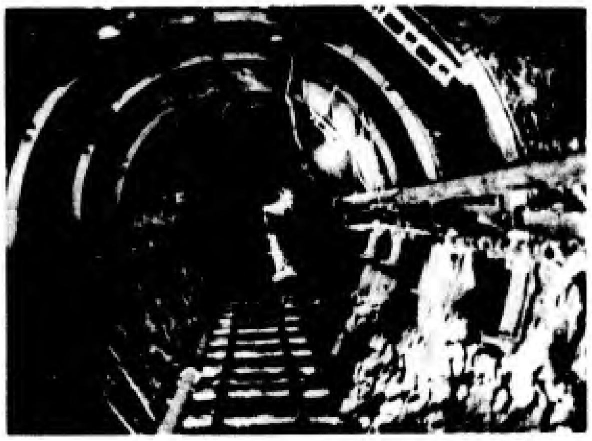
SANDSTONE & SHAL
DETERIOR

MACHINE AT HEADING. NOTE LASER BEAM TARGET

MACHINE HOLED TH

SANDSTONE IN CROWN. SHALE BELOW BEGINNING TO DETERIORATE

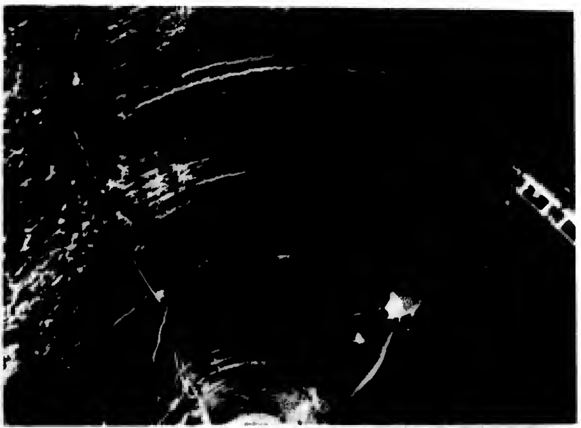
HINE AT PORTAL.
TED CONCRETE
"



SANDSTONE & SHALE SECTION. THE SHALE DETERIORATES RAPIDLY

ASER BEAM TARGET

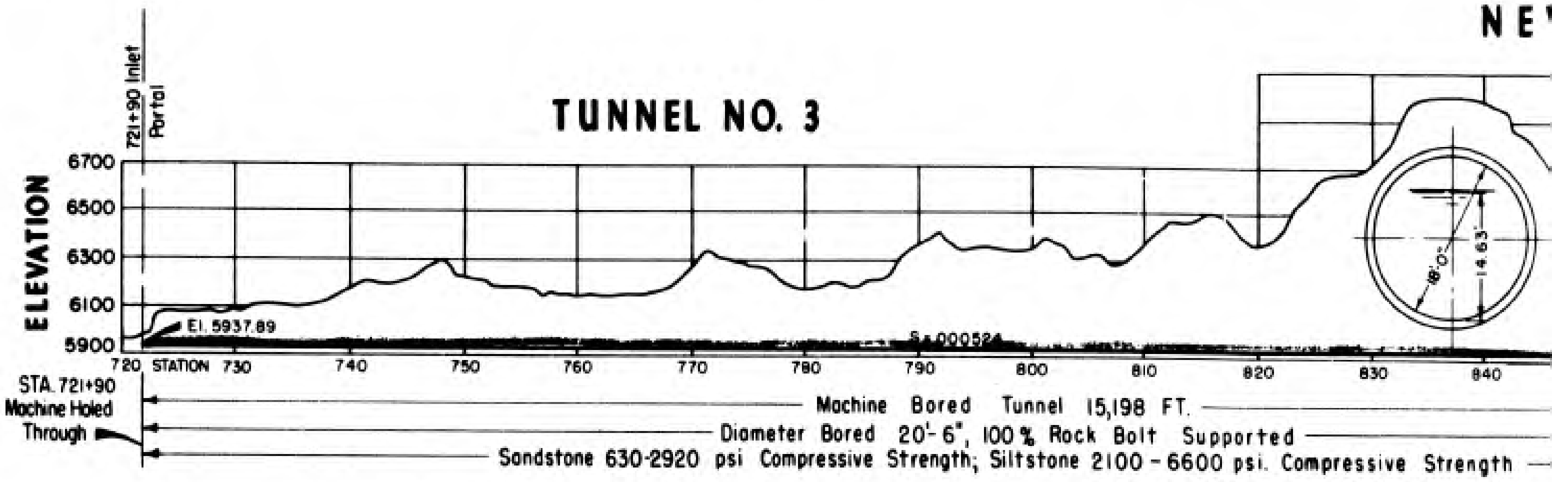
MACHINE HOLED THROUGH AT INLET PORTAL



SANDSTONE IN CROWN. SHALE BELOW BEGINNING TO DETERIORATE

TUNNELS
NAVAJO INDIAN
NE

TUNNEL NO. 3



TUNNE

MACHINE DATA

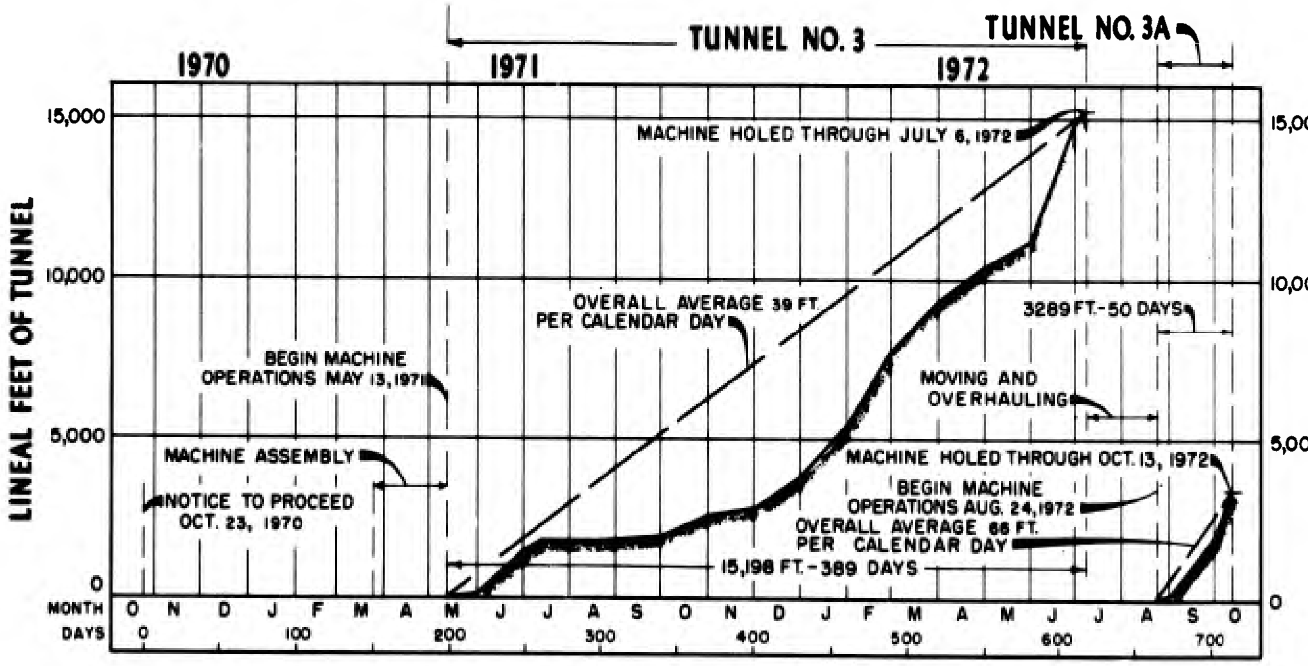
MANUFACTURED BY DRESSER INDUSTRIES INC.__MODEL 205
LENGTH - 58'_____________WEIGHT 460,000 LBS.
FORWARD THRUST CAPABILITY_______1,600,000 LBS.
AVAILABLE TORQUE_______880,000 FT.LBS.@ 6 RPM
CUTTERS______36 DOUBLE DISC & 32 CONICAL PICKS
STROKE______________________4 FEET
4-180 H.P. D.C. MOTORS TO ROTATE HEAD
LASER BEAM GUIDANCE
WASTE DISPOSAL_____TRAILING CONVEYOR & TRAIN
AVERAGE AVAILABILITY____________79 %
SAME EQUIPMENT USED IN BOTH TUNNELS

PROGRESS

	TUNNEL NO. 3	TUNNEL NO. 3A
MAX. RATES		
SHIFT	94 FT.	78 FT.
DAY	260 FT.	180 FT.
AVERAGE RATES		
SHIFT	16.6 FT.	28.9 FT.
DAY	50 FT.	86.6 FT.
AVERAGE PER CALENDER DAY	39 FT.	66 FT.

HYDRAULIC PROPERTIES

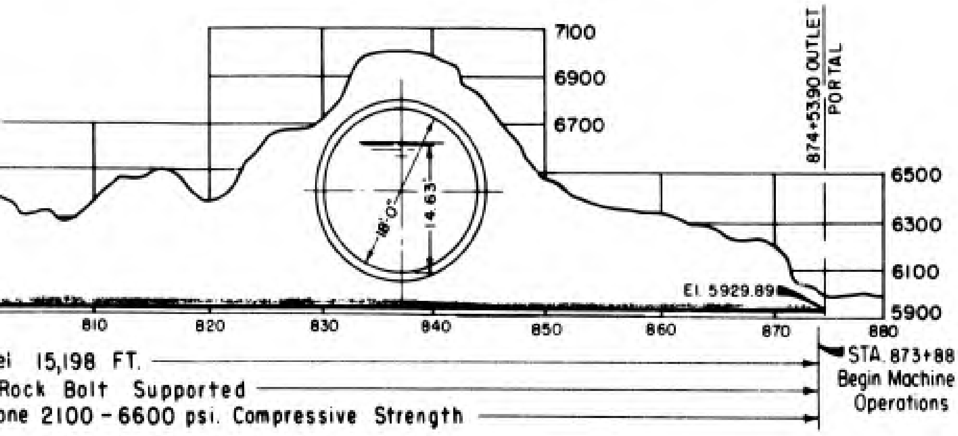
TUNNEL	Q	A	V	r	n	s	d
18'-0" DIA. CONCRETE LINED CIRCULAR	1800	221.55	8.12	5.48	.013	.000524	14.63



TUNNEL MACHINE-PROGRESS CHART

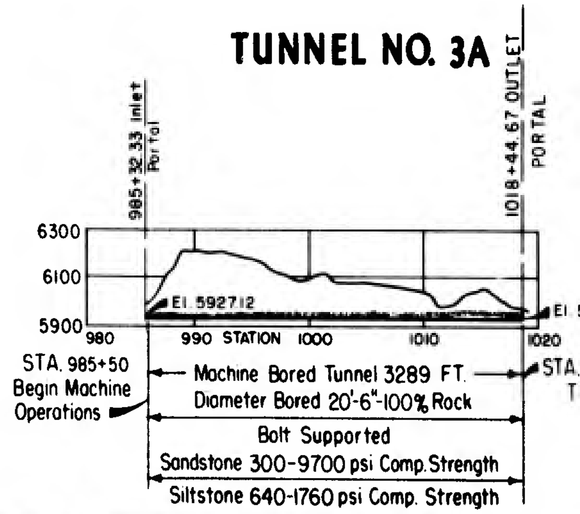
C

TUNNELS NO. 3 & 3A
NAVAJO INDIAN IRRIGATION PROJECT
NEW MEXICO



el 15,198 FT.
Rock Bolt Supported
one 2100 - 6600 psi. Compressive Strength

TUNNEL NO. 3A



STA. 985+50 Begin Machine Operations

Machine Bored Tunnel 3289 FT.
Diameter Bored 20'-6"-100% Rock

Bolt Supported
Sandstone 300-9700 psi Comp. Strength

Siltstone 640-1760 psi Comp. Strength

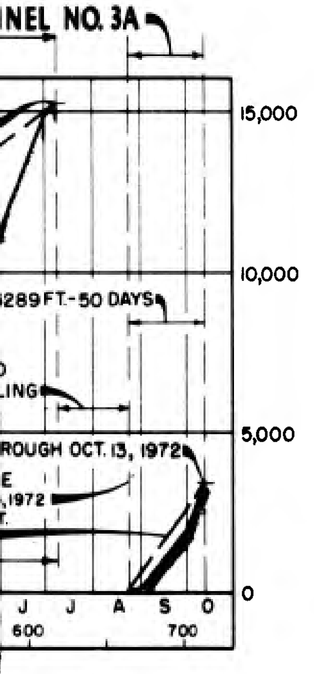
TUNNEL PROFILES

PROGRESS

	TUNNEL NO. 3	TUNNEL NO. 3A
ES		
FT	94 FT.	78 FT.
Y	260 FT.	180 FT.
RATES		
FT	16.6 FT.	28.9 FT.
Y	50 FT.	86.6 FT.
PER CALENDERDAY	39 FT.	66 FT.

HYDRAULIC PROPERTIES

NNEL	Q	A	V	r	n	s	d
. CONCRETE D CIRCULAR	1800	221.55	8.12	5.48	.013	.000524	14.63



ART

CONTRACT DATA

CONTRACTOR-FLUOR UTAH ENGINEERS AND CONSTRUCTORS INC.
SPECIFICATION NO. DC - 6849
BID - $6,783,456 TUNNEL NO. 3
BID - $2,174,097 TUNNEL NO. 3A

MISCELLANEOUS DATA

VENTILATION LINE _______________ 30"
POWER SUPPLY INTO TUNNELS ___ 4160 VOLTS
AMBIENT TEMPERATURE AT CUTTER HEAD ____________ 70° F TO 100° F
ROCK TEMPERATURE ____ 61° F TO 70° F
PRIMARY SUPPORT__RESIN ANCHORED ROCK BOLTS
AVERAGE PER CALENDAR DAY ___ 39 FT. ___ 66 FT.
MINOR WATER ___ CAUSED ROCK DETERIORATION
NO. OF MEN TO OPERATE MACHINE __ 3 PERSHIFT

OUTLET PORTAL TUNNEL NO.3

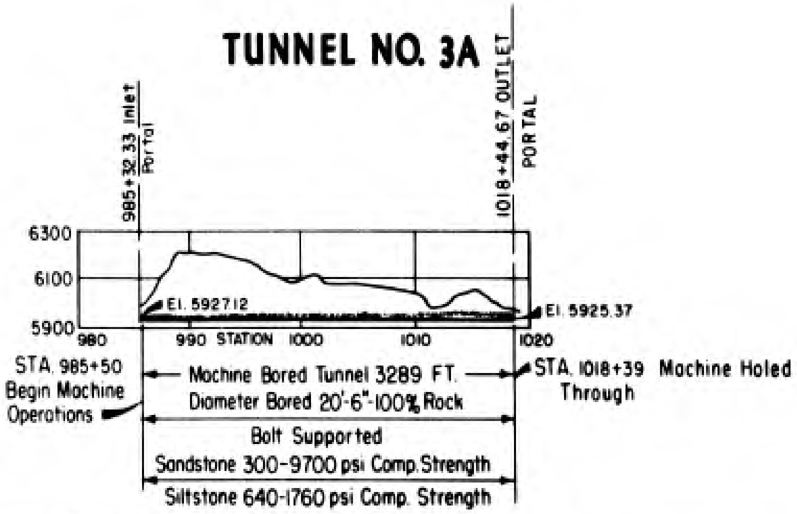
TYPICAL CR
ENCOUN

CUTTER HEAD DRESSER TUNNELING MACHINE

TRAIN LOADING AND CAR TRANSFE

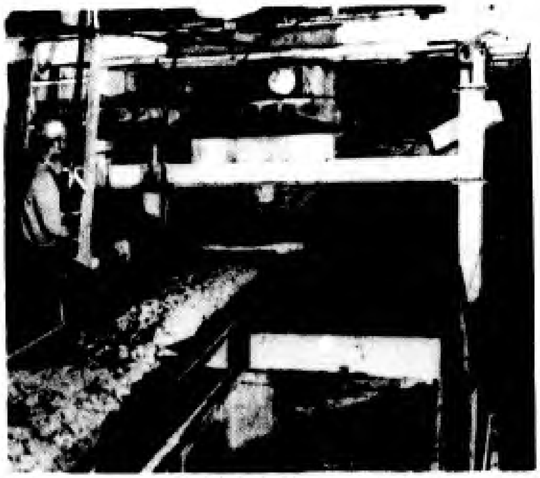
A
ECT

TUNNEL NO. 3A



OUTLET PORTAL TUNNEL NO. 3

TYPICAL CROSSBEDDING & LENSES OF FORMATIONS ENCOUNTERED IN TUNNELS NO. 3 & 3A



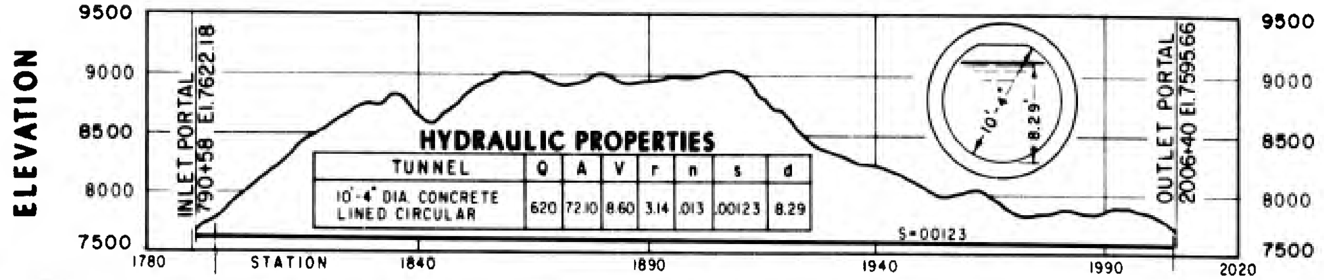
TRAIN LOADING AND CAR TRANSFER STATION

WATER HOL

CENTRAL U

BONNEVIL

TUNNEL PROFILE



HYDRAULIC PROPERTIES

TUNNEL	Q	A	V	r	n	s	d
10'-4" DIA. CONCRETE LINED CIRCULAR	620	72.10	8.60	3.14	.013	.00123	8.29

Machine Holed Through Sta. 1795+73 ← Machine Bored Tunnel 21,043 FT.– Diameter Bored 12'-11", 100% Steel Rib Supported → Begin Machine Operations Sta. 2006+16

← Rock Types - Sandstone, Siltstone, Shale and Conglomerate →

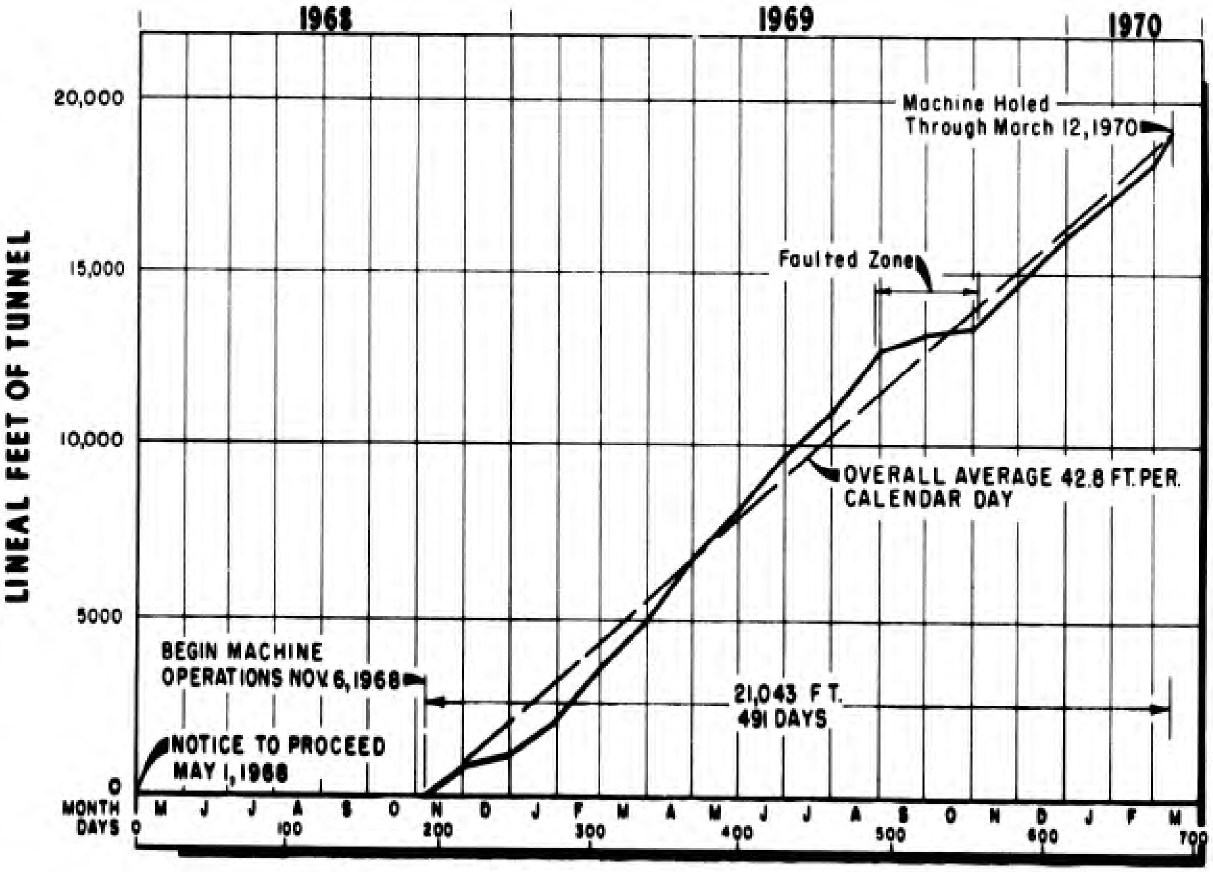
MACHINE DATA

MANUFACTURED BY ROBBINS. THIS MACHINE USED IN AZOTEA TUNNEL (MODIFIED FOR THIS JOB)
LENGTH_______35 FT. WEIGHT 192,000 LBS.
*THRUST 477,000 LBS. *TORQUE 300,000 FT. LBS.
CUTTERS_________1-TRICONE AND 29 DISC
HEAD ROTATED BY 4-100 HP, 440 VOLT MOTORS
LASER BEAM GUIDANCE
WASTE DISPOSAL___TRAILING CONVEYOR & TRAIN

*MAXIMUM CAPABILITY

PROGRESS

MAXIMUM FOR 1 DAY______180 FT.
FOR 1 SHIFT_______77 FT.
AVERAGE PER DAY_______96 FT.
PER SHIFT_______32 FT.
PER CALENDAR DAY__42.8 FT.



Machine Holed Through March 12, 1970

OVERALL AVERAGE 42.8 FT. PER CALENDAR DAY

BEGIN MACHINE OPERATIONS NOV. 6, 1968

21,043 FT. 491 DAYS

NOTICE TO PROCEED MAY 1, 1968

TIME-DATE AND DAYS

TUNNEL MACHINE-PROGRESS CHART

CONTRACT

CONTRACTOR-BOY
DRILLING Co. & GIBBO
SPECIFICATION N
TUNNEL SCHEDULE B

MISCELLANEO

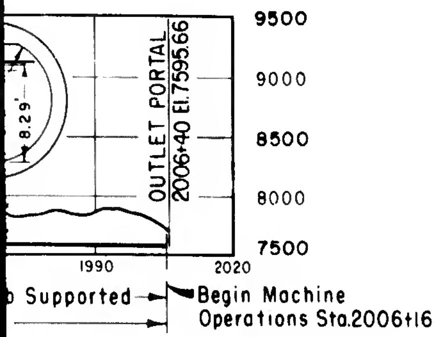
TRACK GAGE_____
VENTILATION LINE
VOLTAGE SUPPLY IN
____
No. OF MEN TO OPER
__________6
AMBIENT TEMPERATU
HEAD______
MACHINE OPERATED
_3 SHIFT DAY,

2

TER HOLLOW TUNNEL

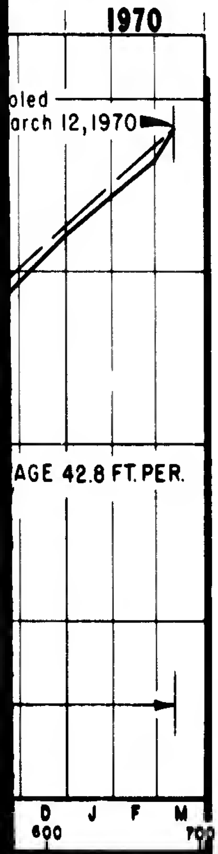
CENTRAL UTAH PROJECT

BONNEVILLE UNIT-UTAH



OGRESS

R I DAY	180 FT.
SHIFT	77 FT.
R DAY	96 FT.
SHIFT	32 FT.
ALENDAR DAY	42.8 FT.



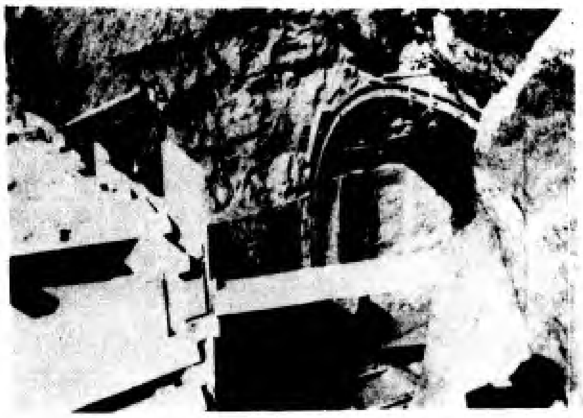
HART

CONTRACT DATA

CONTRACTOR-BOYLES BROS.
DRILLING Co. & GIBBONS AND REED Co.
SPECIFICATION No. DC-6575
TUNNEL SCHEDULE BID $5,236,142

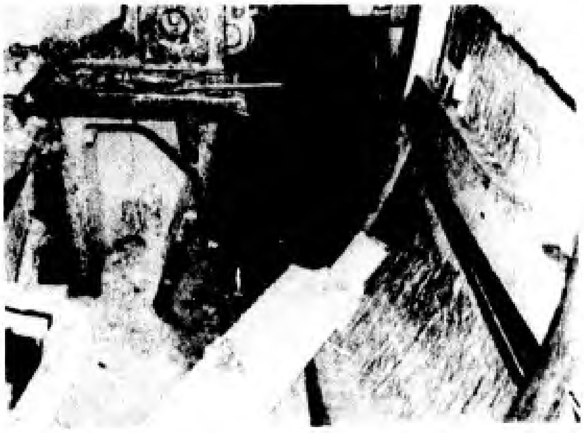
MISCELLANEOUS DATA

TRACK GAGE____________30"
VENTILATION LINE_______24"
VOLTAGE SUPPLY INTO TUNNEL___________4,160 VOLTS
No. OF MEN TO OPERATE MACHINE__________6 PER SHIFT
AMBIENT TEMPERATURE AT CUTTER HEAD____________62° F
MACHINE OPERATED_________3 SHIFT DAY, 4 DAY WEEK



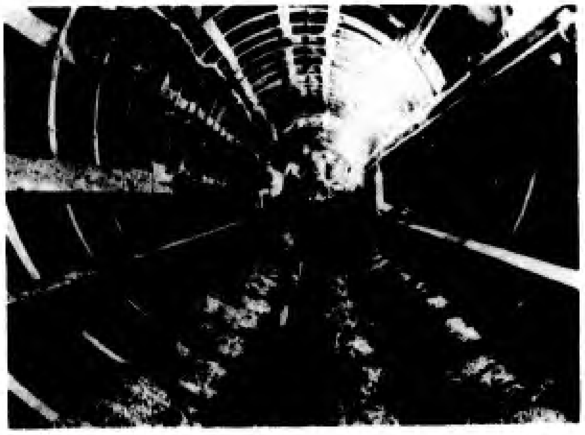
GAP IN CUT AND COVER SECTION AT PORTAL FOR
INSTALLATION OF MACHINE CUTTER HEAD

LOWERING CU OV
INSTALL ON M F
MOVED IN THRO



WATER FLOWING AROUND MACHINE

BORING TH IN
INCO



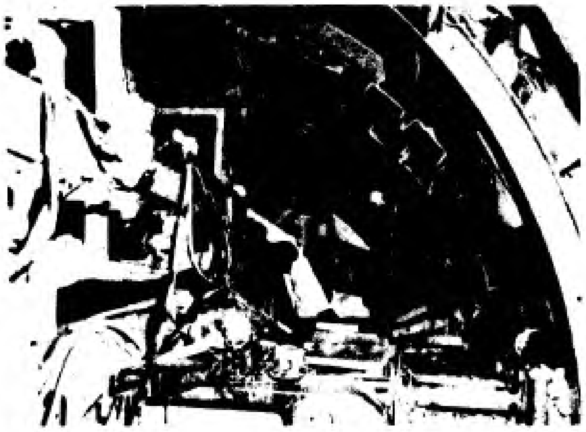
SUBINVERT CONCRETE PLACED
TO PROTECT INVERT ROCK

NNEL

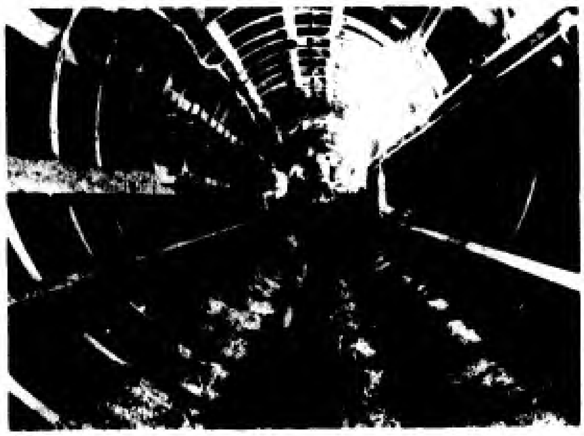
OVER SECTION AT PORTAL FOR
F MACHINE CUTTER HEAD

LOWERING CUTTER HEAD INTO GAP TO INSTALL ON MACHINE BODY WHICH WAS MOVED IN THROUGH THE CUT AND COVER

NG AROUND MACHINE



BORING THROUGH ZONE OF WET INCOMPETENT ROCK



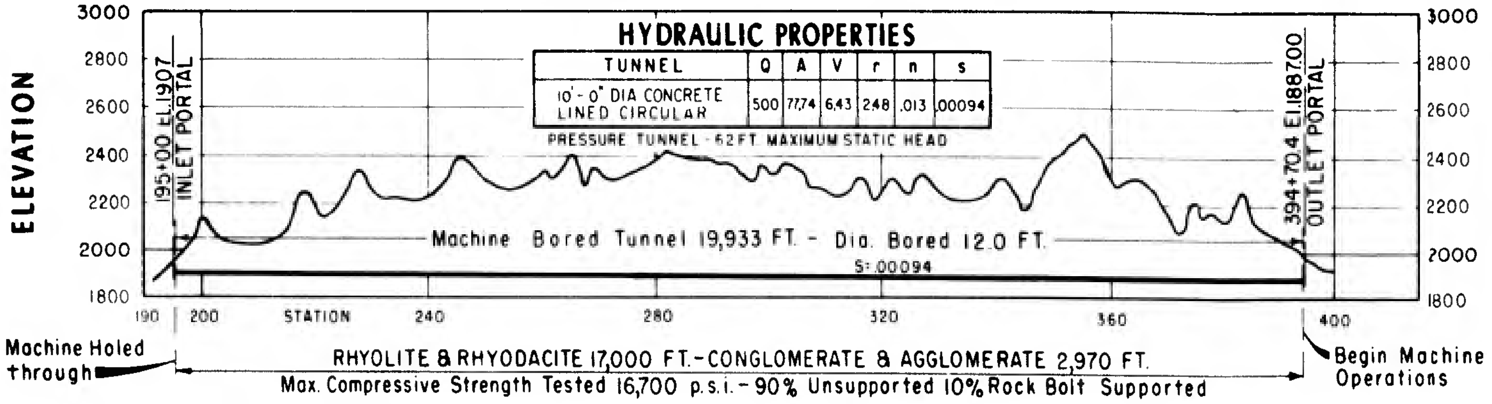
SUBINVERT CONCRETE PLACED TO PROTECT INVERT ROCK

RIVER MOUN

SOUTHERN NEVA

NE

TUNNEL PROFILE



HYDRAULIC PROPERTIES

TUNNEL	Q	A	V	r	n	s
10'-0" DIA CONCRETE LINED CIRCULAR	500	77.74	6.43	2.48	.013	.00094

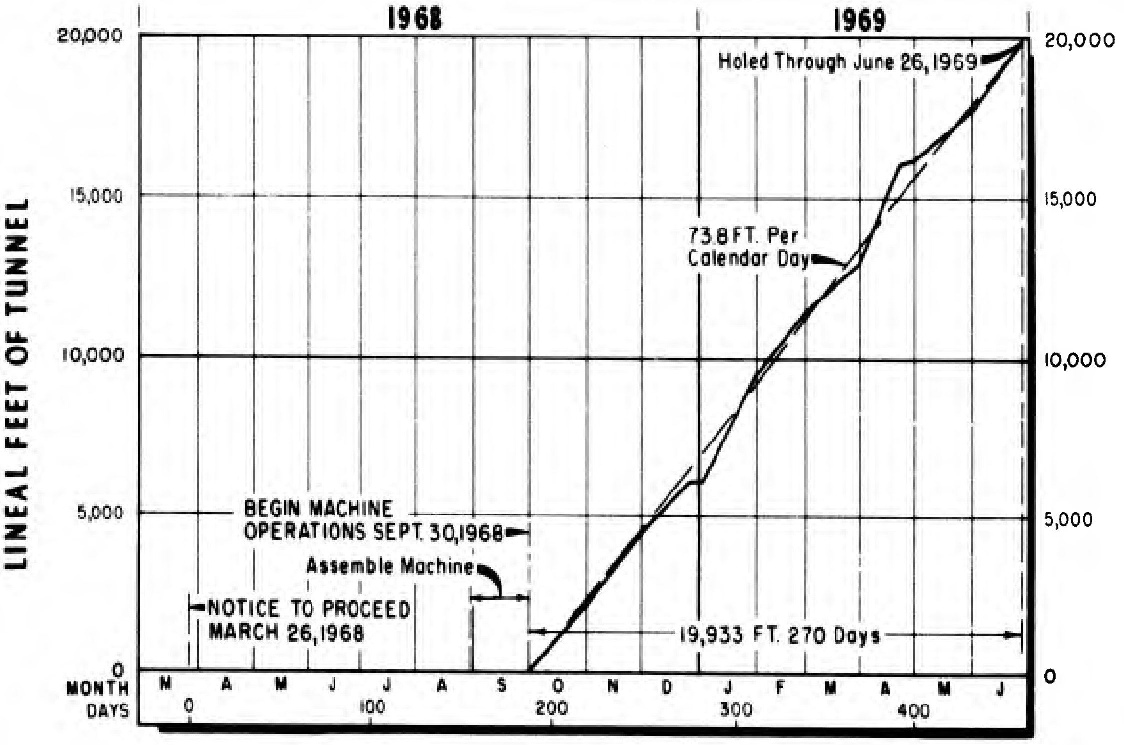
MACHINE DATA

MANUFACTURED BY JARVA MODEL MARK 11-12
LENGTH_________37 FT. WEIGHT 130,000 LBS.
*THRUST___886,000 LBS. *TORQUE 235,000 FT. LBS.
31 CUTTERS, 26 STEEL KERF TYPE, 1 TOOTH TYPE
4 TOOTH OR TUNGSTEN CARBIDE INSERT KERF TYPE AS GAGE CUTTERS
ROTATION BY 4-100 HP ELECTRIC MOTORS, LATER MODIFIED TO 6-50 HP
LASER BEAM GUIDANCE
WASTE DISPOSAL__TRAILING CONVEYOR AND TRAIN

*MAXIMUM CAPABILITY

PROGRESS

AVERAGE___________________73.8 FT. PER CALENDAR DAY
AVERAGE___________________108 FT. PER WORKING DAY
MAXIMUM___________________293 FT. PER DAY
MAXIMUM___________________104 FT. PER 8 HR SHIFT



TUNNEL MACHINE-PROGRESS CHART

CONTRACT D

UTAH CONSTRUCTION AN
DURING CONTRACT PERI
TO FLUOR UTAH ENGIN
CONSTRUCTORS, INC.
SPECIFICATION No.
BID (TUNNEL PORTION)

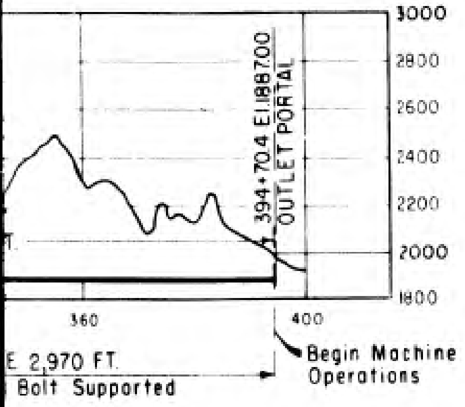
MISCELLANEOUS

TRACK GAGE_________
VENTILATION LINE____
VOLTAGE SUPPLY INTO TU
_____________4,1
No. OF MEN TO OPERATE
_____________4
AMBIENT TEMPERATURES
HEAD__________95
ROCK TEMPERATURE___

IVER MOUNTAINS TUNNEL

SOUTHERN NEVADA WATER PROJECT

NEVADA



PROGRESS

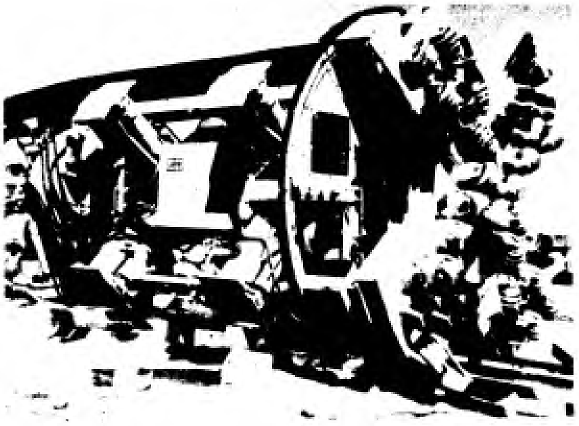
3.8 FT. PER CALENDAR DAY

108 FT PER WORKING DAY

------293 FT. PER DAY

---104 FT. PER 8 HR SHIFT

OVERALL VIEW-OUTLET PORTAL
WORK AREA



VIEW OF JARVA MACHINE DURING ASSEMBLY

LAS

BREAK THROUGH

CHAN

CONTRACT DATA

UTAH CONSTRUCTION AND MINING - DURING CONTRACT PERIOD CHANGED TO FLUOR UTAH ENGINEERS AND CONSTRUCTORS, INC.

SPECIFICATION No. DC-6595

BID (TUNNEL PORTION) $ 3,572,128

MISCELLANEOUS DATA

TRACK GAGE--------------24"

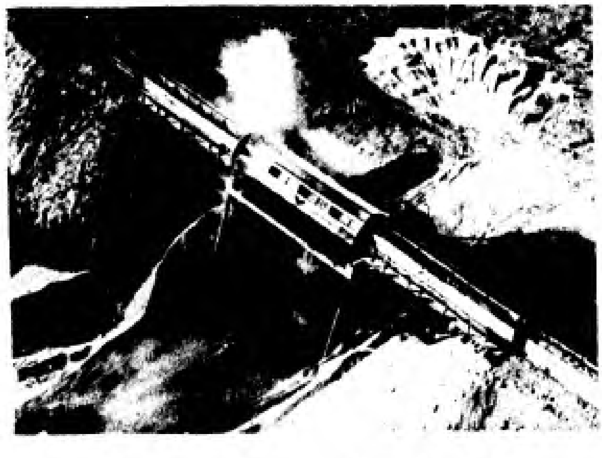
VENTILATION LINE---------30"

VOLTAGE SUPPLY INTO TUNNEL--------------4,160 VOLTS

No. OF MEN TO OPERATE MACHINE------------4 PER SHIFT

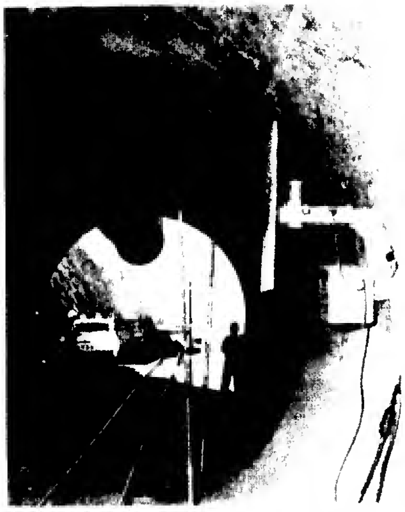
AMBIENT TEMPERATURES AT CUTTER HEAD---------95° TO 105° F

ROCK TEMPERATURE--------82° F

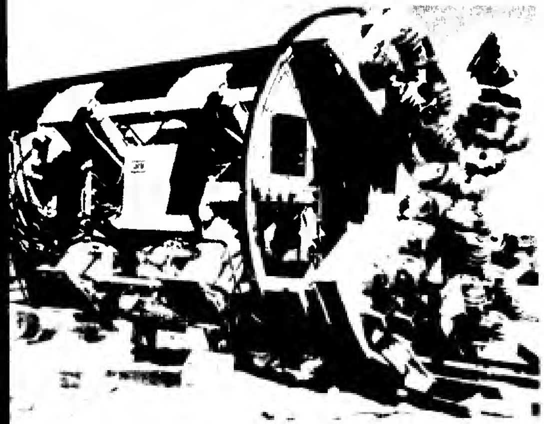


WASTE DISPOSAL-ROTARY CAR
DUMP IN OPERATION

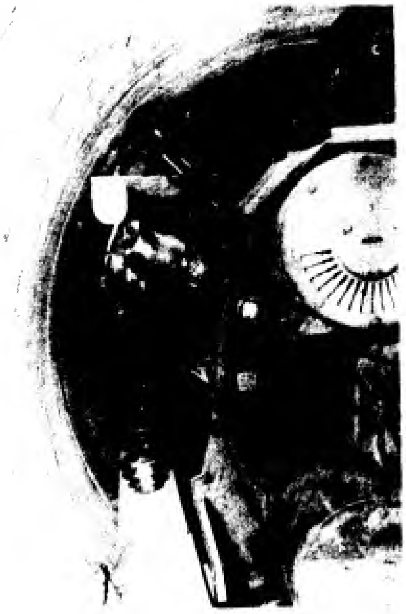
ASSEMBLING M
WITH VENTIL



LASER BEAM GUN MOUNTED ON TUNNEL WALL



EW OF JARVA MACHINE DURING ASSEMBLY



CHANGING CUTTERS-LASER TARGETS IN UPPER QUADRANT

BREAK THROUGH

POSAL-ROTARY CAR
IN OPERATION

ASSEMBLING MACHINE-NOTE CONVEYOR WITH VENTILATION SYSTEM ON TOP

APPENDIX D: GLOSSARY OF TERMS USED IN UNDERGROUND EXCAVATION

adit - a nearly horizontal passage leading from the surface to an underground chamber or a passage connecting two such chambers.

ammonium nitrate (AN) - ANFO (AN-FO) - ammonium nitrate mixed with fuel oil (approximately 94 percent to 6 percent, respectively, by weight) used as an explosive in rock excavation.

back - roof or upper part of a stope, drift, or tunnel.

back-packing - any granular material which is used to fill the empty space between lagging and rock surface.

bench - a berm or block of rock within the final outline of a tunnel which is left after a top heading has been excavated.

bit - a star or chisel-pointed tip forged or screwed (detachable) to the end of a drill steel.

blasting agent - a substance or mixture of substances capable of being detonated, but of low sensitivity, so that in general its reaction cannot be initiated by a No. 8 blasting cap.

blind bore - a shaft or hole bored without use of a pilot hole. Also, "blind hole": a hole open only at one end.

blocking - wood blocks placed between the excavated surface of a tunnel and the bracing system.

bootleg or socket - that portion or remainder of a shothole found in a face after a blast has been fired.

boxhole boring - the method of boring a blind hole from the bottom up.

brattice (brattishing) - a partition formed of planks or cloth in a shaft or gallery for controlling ventilation.

breasting - boards placed against the heading (breast) of a drift to prevent sloughing. The breasting itself is usually supported by one or several vertical soldiers, each held in place by a raker, or strut sloping back to the floor.

bridge action time - the time between firing the shot and the time the first installment of rock drops out of the roof without provocation.

bulkhead - a partition built in an underground structure or structural lining to prevent the passage of air, water, or mud.

burn cut (also shatter cut or Michigan cut) - cut holes for tunnel blasting which are heavily charged, close together, and parallel. About four cut holes are used which produce a central, cylindrical hole of completely shattered rock. The central, or burn cut provides an excellent free face for breaking rock with succeeding blasts.

cage - a box or enclosed platform used for raising or lowering men or materials in a shaft.

California switch - a movable double track set on top of the regular track so that cars can pass one another in approaching the working face.

camouflet - the underground cavity produced by a fully contained explosive.

center core method - a sequence of excavating a tunnel in which the perimeter above the invert is excavated first to permit erection of the initial lining. One or a series of side and crown drifts may be utilized. The center core is excavated after the initial lining is installed.

cherry picker - a gantry crane which is used in large tunnels to pick up muck cars and shift a filled car from a position next to the working face over other cars to the rear of the train.

collar - that portion of a shaft extending from the surface to bedrock.

collar bracing - pieces of timber which are set in line between successive ribs to furnish lateral support to the ribs.

concrete-as-you-go - a sequence of placing the final concrete lining as soon as a monolith length is excavated. This sequence shortens the length of exposed tunnel initially supported.

competent rock - this term has a relative, as opposed to a precise, meaning: rock which is adequate with respect to the purpose at hand. In tunneling, competent rock has sufficient stand-up time to allow completion of support installation as in most of a particular tunnel drive. In some situations this implies that no support or reinforcement is required except perhaps a final lining installed months later.

convergence - the movement of the surfaces of an underground excavation toward each other. Convengence measurements are used to detect unstable conditions.

cover - the perpendicular distance from a point in a tunnel to the ground surface.

crown - the highest point of an arched tunnel cross section. The term is also used to designate the arched roof above spring line. Also called the "roof" or "back."

cut-and-cover - a sequence of construction in which an open trench is excavated, the tunnel or conduit section is constructed, then covered with backfill.

deflagration - a process of fast burning. When the reaction front travels linearly through an explosive material at high but subsonic speeds, the material is said to deflagrate.

delays - detonators which explode at a suitable fraction of a second after passage of the firing current from the exploder. Delays are used to insure that each charge will fire into a cavity created by earlier shots in the round.

density - weight per unit volume, usually expressed in grams per cubic centimeter (numerically equivalent to specific gravity).

detonation - the process that occurs when explosive material or materials react chemically extremely fast. If the reaction front travels linearly through the explosive substance at supersonic speed, the process is called detonation.

detonation pressure - pressure behind the detonation front in an exploding charge, usually expressed in kilobars.

detonation velocity - the speed at which a detonation wave travels through a body of explosive, expressed in linear velocity units, e.g., feet per second.

drift - an approximately horizontal passageway or portion of a tunnel. In the latter sense, depending on its location in the final tunnel cross section, it may be classified as a "crown drift," "side drift," "bottom drift," etc. A small tunnel driven ahead of the main tunnel.

drifter - a rock drill mounted on column, bar, or tripod, used for drilling blast holes in a tunnel face. Patented by J. G. Leyner, 1897.

drill steel - see steel, drill.

drive - to excavate horizontally or approximately horizontally. An underground opening so excavated.

dynamite - a highly explosive material whose primary explosive ingredient is nitroglycerine (NG). Collectively, "dynamites" can refer to a group of NG-based explosive products, such as straight dynamite, ammonia dynamite, and blasting gelatin.

emulsion - see "water gel."

extensometer - an instrument used for measuring small deformations, displacements, or deflections.

extrados - the exterior curved surface of an arch.

extruded liner - a liner produced by a slipforming system which is an integral part of a tunnel boring machine.

face - the advance end or wall of a tunnel, drift, or other excavation at which work is progressing.

final ground or rock support - support placed to provide permanent stability, usually consisting of rock reinforcement, shotcrete, or concrete lining. The lining may also be required to improve fluid flow, assure water tightness, or improve appearance of tunnel surface.

fire damp - methane (CH_4) - also called explosive gas or marsh gas. It may be encountered in coal regions, often is associated with shales, and occurs in the neighborhood of oil fields or rock salt deposits.

forepole - a pointed board or steel rod driven ahead of timber or steel sets for temporary excavation support.

forepoling - driving forepoles ahead of the excavation, usually supported on the last set erected, and in an array which furnishes temporary overhead protection while installing the next set.

fume class - a measure of the production of poisonous gases by the explosive's detonation, commonly expressed in qualitative terms, e.g., good, poor.

galloway - a work platform (single or multideck) suspended in a shaft during sinking operations.

gouge zone - a layer of fine, wet, clayey material occurring near and at either side of a fault.

grasshopper a device for positioning muck cars for loading such that empty cars pass toward the face over filled cars to the muck loader.

grout - a liquid chemical mix which may set to form either a solid or a gel, a neat cement slurry, or a mix of equal volumes of cement and sand which is poured into joints in masonry or injected into rocks. Also used to designate the process of injecting joint-filling material into rocks.

gunite - see shotcrete.

heading - the wall of unexcavated rock at the advance end of a tunnel. Also used to designate any small tunnel and a small tunnel driven as a part of a larger tunnel.

heat of detonation (energy) - theoretical total energy released by the chemical reaction occurring when an explosive detonates, usually expressed in calories per gram.

hook load - the weight of a drill string that a drill rig can lift.

inby - away from the shaft or portal of a tunnel toward the heading.

initial ground or rock support - support required to provide stability of the tunnel opening, installed directly behind the face as the tunnel or shaft excavation progresses, and usually consisting of steel rib sets, shotcrete, or rock reinforcement or a combination of these.

initiation system - the means by which an explosive charge is caused to detonate.

intrados - the interior curved surface of an arch.

invert - the lowest point on the cross section of an underground passage or the lowest section of the lining consisting essentially of the floor paving.

jumbo - a movable machine containing working platforms and drills, used for drilling and loading blast holes, scaling the face, or performing other work related to excavation.

lagging - londitudinal supporting members such as boards or steel channels placed between bracing and the rock surface.

lifters - shot holes drilled near the floor of a tunnel and fired after the cut holes and relief holes.

liner plates - pressed steel plates installed between the webs of the ribs to make a tight lagging, or bolted together outside the ribs to make a continuous skin.

load cell - an instrument which consists of a deformable body (usually cylindrical) and a means of measuring deformation, which can be positioned to carry load where the load is transferred to a support or to carry the load where elements of a support structure react against each other. The measured deformation of the load cells body can be scaled to indicate the magnitude of the imposed load.

low explosive - a substance or mixture of substances capable of deflagration but not of detonation.

mining - the process of digging below the surface of the ground to extract ore or to produce a passageway such as a tunnel.

mole - popular name for a continuous, full-face, tunnel boring machine.

muck - broken rock or earth excavated from a tunnel or shaft.

open cut - any excavation made from the ground surface downward.

outby - away from the working face toward the shaft or portal.

overbreak - the quantity of rock that is actually excavated beyond the perimeter established as the desired tunnel outline.

pattern reinforcement or pattern bolting - the installation of reinforcement elements in a regular pattern over the excavation surface.

penstock - a pressure pipe which conducts water to a power plant.

perfo sleeve - two perforated half round sections of sheet metal which are filled with grout, wired together, and installed in a hole. A steel bar with a rounded nose is forced inside the sleeve, causing the grout to squeeze through the perforations and bond to the sides of the hole.

pilot drift (pilot tunnel) - a smaller drift or tunnel driven in advance of the main tunnel, used to investigate rock conditions prior to the major excavation, or to permit installation of reinforcement before the principal mass of rock is removed.

pilot shaft (pilot hole) - a smaller hole constructed prior to excavation of the main shaft and usually centered on it to serve the purpose of providing: a passageway for muck to fall during the main excavation; a means of connecting the boring machine on the surface with the cutterhead at the lower end, in raise-boring operations; and information on rock conditions prior to the main excavation.

popshooting or popping - boulder blasting by drilling, charging, and firing a hole in the center of a boulder.

portal - the entrance from the ground surface to a tunnel.

powder - any dry explosive.

prestressed rock anchor or tendon - tensioned reinforcing elements, generally of higher capacity than a rock bolt, consisting of a high-strength steel tendon (made up of one or more wires, strands, or bars) fitted with a stressing anchorage at one end and a means of permitting force transfer to the grout and rock at the other end.

primary lining - the lining first placed inside a tunnel or shaft, essentially for providing initial support.

primary support (or reinforcement) - support or reinforcement required to maintain stability of an underground excavation during construction.

pull - the advance during the firing of each complete round of shot holes in a tunnel.

pyramid cut - a method of blasting in tunneling or shaft sinking in which the holes of the central ring (cut holes) outline a pyramid, their toes being closer together than their collars.

raise - to drill, bore, or otherwise excavate from the lower end. Also, a shaft excavated upward (vertical or sloping). It is usually cheaper to raise a shaft than to sink it since the cost of shoveling away is negligible when the slope of the raise exceeds 40 degrees from the horizontal.

recessed rock anchor - a rock anchor placed to reinforce the rock behind the final excavation line after a portion of the tunnel cross section is excavated but prior to excavating to the final line.

relievers - the holes which are fired after the cut holes and before the lifter holes or rib holes.

rib - an arched individual frame, usually of steel, used in tunnels to support the excavation. Also used to designate the side of a tunnel.

rib holes - holes which are drilled at the side of the tunnel or shaft and fired last, i.e., after the cut holes, relief holes, and lifter holes (if any).

roadheader - a vehicular partial-face tunnel excavation machine which is equipped with a powered cutterhead supported by an articulated boom. Most such machines have provision for mucking operations.

rock anchor - an untensioned reinforcement element consisting of a rod embedded in a mortar or grout-filled hole. See "prestressed rock anchor."

rock bolt - a tensioned reinforcement element consisting of a rod, a mechanical or grouted anchorage, and a plate and nut for tensioning by torquing the nut or for retaining tension applied by direct pull.

rock burst - violent failure of rock such as to endanger men or equipment.

rock dowel - see "rock anchor."

rock reinforcement - rock bolts, prestressed rock anchors, untensional rock dowels, or wire tendons installed at a fairly uniform spacing in a rock mass to consolidate the rock and reinforce the rock's natural tendency to support itself. Also used to refer to shotcrete on rock surface.

rock support - supports such as wood sets, steel sets, or reinforced concrete linings installed to provide resistance to inward movement of rock toward the excavation.

round - a group of holes fired at essentially the same time. The term is also used to denote a cycle of excavation consisting of drilling blast holes, loading, firing, and then mucking.

running ground - rock that readily falls into underground openings.

sandhog - one who works, usually in a compressed air caisson, in digging underwater tunnels.

scaling - the removal of loose rock adhering to the solid face after a shot has been fired. A long scaling bar is used for this purpose.

scrubber - a device placed on diesel exhaust systems to control toxic fumes.

secondary lining (secondary support) - the second-placed (or final) lining which is installed to provide an interior surface appropriate to the use of the tunnel or shaft, provide for longterm stability of the ground, and/or to control inflow or escape of water.

sensitivity - a measure of the energy required to initiate detonation of an explosive, usually expressed in terms of what strength of blasting cap will initiate the explosive under standardized test conditions.

set - the assemblage of bracing placed at one point in a tunnel as initial support.

shaft - an elongate linear excavation, usually vertical, but may be excavated at angles greater than 30 degrees from the horizontal; see "tunnel."

shield - a movable steel framework or canopy which furnishes protection to workers or equipment. The earliest applications included working platforms for miners and supported the face.

shotcrete - as defined by the American Concrete Institute, includes both pneumatically applied mortar and pneumatically applied concrete. In tunneling practice and literature, the term is most often used for pneumatically applied concrete only.

skip - a metal box for carrying rock which is moved vertically or along an incline.

slashing - enlarging an existing opening by use of blast holes drilled parallel or nearly parallel to the free surface.

slickenside - polished and striated surface resulting from friction of movement along a joint.

slurry - see "water gel."

spall - a chip or splinter or rock. Also, to break rock into smaller pieces.

spiles - pointed boards or steel rods driven ahead of the excavation. (same as forepoles).

spot reinforcement or spot bolting - the installation of reinforcement elements in localized areas of rock instability or weakness as determined during excavation. Spot reinforcement may be in addition to pattern reinforcement or internal support systems.

spring line - the point where the curved portion of the roof meets the top of the wall. In a circular tunnel, the spring lines are at opposite ends of the horizontal center line.

squeezing ground - ground that slowly moves into an underground opening without fracturing.

stand-up time - see "bridge action time."

steel, drill - a chisel or star pointed steel rod used in making a hole in rock for blasting. The rod is struck by a sledge hammer swung by one man, and rotated between successive hammer blows by a second man or helper. A steel rod used to transmit thrust or torque from a power souce to the drill bit.

stemming - material used for filling a blasting hole to confine the charge of explosive. Damp sand, damp sand mixed with clay, or gypsum plaster are examples of materials used for this purpose.

stope - an inclined excavation driven from the main tunnel or drift in an upward direction. Excessive overbreak in the crown of a tunnel, if occurring in only a short distance, is sometimes referred to as a stope.

stoper - rock drill for upward drilling. Patented by C. H. Shaw in 1890.

swelling ground - a rock or soil that expands when wet.

TBM - tunnel boring machine; see "mole."

tight - rock remaining within the minimum excavation lines after completion of a round--that is, material that would make a template fit tight. "Shooting tights" requires closely placed and lightly loaded holes.

tremie - a watertight pipe for subaqueous placement of concrete. The bottom of the pipe is kept slightly below the surface of the concrete and a column of concrete is maintained in the pipe by feeding concrete through a hopper at the upper end.

tunnel - an elongate, narrow, essentially linear excavated underground opening with a length greatly exceeding its width or height. Usually horizontal but may be driven at angles up to 30 degrees from the earth's surface.

walker - one who supervises the work of several gangs.

water gel, slurry, emulsion - these are nearly, though not quite synonymous terms referring to a large group of AN-based blasting agents containing water, all having complex chemical formulations. Their sensitivities vary; some are, many are not, cap-sensitive (referring to initiation by a No. 8 blasting cap). There has been active research and development in the explosives industry over the past two decades, leading to a wide variety of products on the market from different manufacturers. Unfortunately, also, this has given rise to a confusing terminology, in which it is often difficult to compare one product with another.

water resistance - the capacity of an explosive to withstand water penetration and to detonate reliably after exposure to water. Usually expressed in qualitative terms, e.g., excellent, good, poor.

water table - the upper limit of the ground saturated with water.

winze - a steeply inclined passageway connecting one underground working with a lower one, excavated downward.