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The Robbins Company

REPORT

TUNNELING COST REDUCTION STUDY

prepared for

FERMI NATIONAL ACCELERATOR LABORATORY

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1. INTRODUCTION

Fermi National Accelerator Laboratories has a need to review the costs of constructing the very long tunnels which would be required for housing the equipment for the proposed Very Large Hadron Collider (VLHC) project. Current tunneling costs are high, and the identification of potential means of significantly reducing them, and thereby helping to keep overall project costs within an acceptable budget, has assumed great importance.

Fermilab has contracted with The Robbins Company to provide an up-to-date appraisal of tunneling technology, and to review the potential for substantially improving currently the state-of-practice performance and construction costs in particular. The Robbins Company was chosen for this task because of its long and successful experience in hard rock mechanical tunnel boring. In the past 40 years, Robbins has manufactured over 250 tunneling machines, the vast majority for hard rock applications. In addition to also supplying back-up equipment, Robbins has recently established a division dedicated to the manufacture of continuous conveying equipment for the efficient support of tunneling operations.

The study extends beyond the tunnel boring machine (TBM) itself, and into the critical area of the logistics of the support of the machine as it advances, including manpower. It is restricted to proven methods using conventional technology, and its potential for incremental but meaningful improvement, rather than examining exotic and undeveloped means of rock excavation that have been proposed from time to time by the technical community.

This is the first phase of what is expected to be a number of studies in increasing depth of technical detail, and as such has been restricted to the issues connected with the initial 34 kilometer circumference booster tunnel, and not the proposed 500 kilometer circumference tunnel housing the VLHC itself. The booster tunnel is entirely sited within low to medium strength limestone and dolomite formations, typical of the Chicago area. The rock is generally competent with widely spaced jointing, and slowdown of the operation for the installation of rock support is expected to be minimal. The tunneling system will have to be equipped with the necessary equipment for an efficient response to poor rock conditions however.

Because the ground conditions are expected to be very favorable, a state-of-the-art TBM should have no difficulty in excavating at a high penetration rate of 10 meters per hour or more in rock of the average of the range of strengths stated to exist. Disc cutter changes will be few as the rock has very low abrasivity. However, experience has shown that overall tunneling rates are a relatively low percentage of the machine's penetration rate capability. Therefore the main focus of improvement is guaranteeing that the support systems, including mucking and advance of the utilities do not impede the operation. Improved mechanization of the support systems, along with automation where practicable to reduce manpower, is seen as the best means of raising the overall speed of the operation, and reducing its cost.

The first phase of the study is mainly involved with establishing the baseline for current performance, and in identifying areas of improvement. It contains information on existing machine design concepts and provides data on many aspects of the mechanical tunneling process, including costs and labor requirements. While it contains suggestions for technical improvements of the various system, the time limitations of this phase have not permitted any detailed concept development. This should be a major part of the next phase.

2. DEFINITIONS OF TERMS USED IN THE REPORT

Tunnel Boring Machine (TBM) A self-contained and self-propelled structure equipped with a rotary boring head (usually equipped with a number of disk cutters) for the excavation of rock or soil. The excavated material is passed through the structure for delivery to means of transport from the tunnel.

Disk Cutter A hardened steel disk with a narrow edge, mounted on the cutterhead, which is forced to roll under a high thrust load in order to fracture the rock .

Back-up System A collection of equipment trailing immediately behind the TBM which supports the machine itself and the excavation process. The equipment includes systems for electrical and hydraulic supply, muck handling, tunnel support material handling, and ventilation.

Penetration Rate or Instaneous Penetration Rate (IPR) The instantaneous forward speed of the TBM as determined by the product of the number of cutterhead revolutions per minute, and the penetration into the rock per revolution by the cutterhead.

Penetration per Revolution (Prev) The penetration into the rock as determined by the type and condition of the rock, the thrust loading on the cutters, and the cutter dimensions.

Advance Rate or Overall Advance Rate (AR) The net advance rate of the system (usually expressed in meters or feet per hour) as influenced by periods when the machine is not boring for various reasons. Related to utilization.

Utilization (U) The percentage of overall working shift time that the machine is actually boring. It does not include non-working weekend and vacation time. Time for regripping, cutter changing, waiting for muck transport, maintenance and repair time is included.

Availability. The percentage of time that the TBM is available for use when all other supporting systems are ready for operation. It is a measure of the efficiency of the individual machine, and not the complete system.

3. TUNNELING SYSTEM REVIEW

3.1 Comparison of Available Tunneling Methods

Today, the TBM is the undisputed choice for boring long, circular section tunnels in most rock masses. In comparison with the other choices, drill and blast excavation, and so-called roadheading machines, it has a far higher production rate, and requires a small operating crew working in very safe conditions. For short tunnels, because of high capital cost, and the relatively long time required for mobilization and demobilization of the equipment, the TBM is generally considered to be uncompetitive. With the lowering of TBM costs, and the increase in the inventory of available used machines, however, the actual minimum length of tunnel on which it is economically feasible to use a TBM has decreased over the years.

The basic advantages of the other methods are that they offer great flexibility in tunnel cross-section and curvature, can be mobilized quickly, and have lower capital costs. Because there will always be a need for short tunnels and caverns, both these methods will continue to be used and are not threatened by the TBM. They also continue to be used for long tunnels where unstable or squeezing ground may trap or block the operation of a full face TBM. Drill and blast equipment and roadheading machines, unlike TBMs, do not impede access to the tunnel face, which can be therefore more easily stabilized by mechanical or chemical means. However, developments in flexibly shielded TBMs are expected, which will expand the TBM's reliable range of operation into these difficult rock conditions.

If the completed tunnel requires a flat floor, this is normally accommodated by the placement of pre-cast concrete segments, or by using a portion of the excavated rock, if it can be suitably consolidated. In tunnels of 12-foot diameter and less the segment approach will generally be the most efficient and reliable, as the segments are relatively small and easy to handle. An alternative means of obtaining a flat floor would be to remove the lower corners. This has been done in some tunnels, either by drill and blast, or by use of a roadheader after the TBM and back-up system had passed by. Concepts for immediate corner cutting by mounting auxiliary cutting tools directly on the TBM have been studied in the past, but none are known to have actually been employed, owing to the complication of the design.

<u>Drill and Blast Description</u>

The rock is excavated by explosive charges. Holes of approximately 2 inches in diameter are drilled some feet deep into the bedrock. This process is largely automated by the use of self-propelled drill rig vehicles called "jumbos". These can simultaneously drill a number of holes on a large face. After drilling, explosive charges are inserted in the holes and detonated. A mucking vehicle scoops the fragmented rock up. The operation is cyclical. The drilling equipment and the operators have to withdraw to a safe location prior to detonation, and time is lost while waiting for the evacuation of the fumes generated by the explosion. Access has to be provided for the mucking vehicle. One inherent disadvantage in the blasting approach is obtaining a smooth profile is very difficult, and overbreaks occur. This has two results; if the tunnel is to be lined additional concrete is needed to fill the voids, and the rough and fractured rock wall may lead to instability and rock falls, requiring additional support. In contrast the TBM, at least in good quality rock, leaves a very smooth and accurately controlled surface. "Smooth blasting" techniques have been introduced with the intention of reducing overbreak, but these require special attention and are time consuming. Blasting is effective in very high strength rock.

Roadheader and Mobile Miner Description

The roadheader is a highly mobile excavation machine, equipped with one or more boom mounted rotating cutterheads which disintegrate the rock. The machine operator normally controls the boom position, although automatic systems can be used, mainly to control the final tunnel profile. The cutterhead is fitted with drag or ripping type tools, which limits the strength of the rock that can be excavated to the order of 80 to 100 Mpa UCS (unconfined compressive strength), unless it is already highly fractured. The cutterhead is relatively small, and thus only a limited amount of power can be applied to it. In addition, the specific energy of excavation when using drag type tools is higher than that of disk cutting. These factors immediately limit the advance rate potential of the machine very significantly when compared to the full face TBM excavation process. Some machines are equipped \with more than one boom to improve productivity. The excavated rock falling to the tunnel floor is removed by gathering arms or star wheels on the front apron of the machine, and delivered to a conveyor running under the machine. The majority of roadheaders are mounted on tracked or wheeled vehicles, but can be mounted in shields for use in less stable ground conditions.

The mobile miner was introduced to extend the use of the roadheader principle to very hard rock. The cutterhead is very much larger and is equipped with TBM type disk cutters. The cutting action on this machine requires significantly higher forces than that experienced on the normal roadheader, resulting in a much sturdier and heavier platform to absorb and react the loading. So far, the costly additional structural requirements of this concept have made it economically unattractive. Although the mobile miner is a higher powered machine than the roadheader it still only attacks a portion of the face at any one instant, and is therefore limited to a fraction of the performance of the TBM.

Table 1 summarizes the comparison of the alternate methods described. Table 2 shows how TBM capability, in terms of cutter size, thrust, and power has increased since the initial general acceptance of the hard rock TBM some 35 years ago.

3.2 Current TBM Performance Capability in Comparable Geologies

The 34 km booster tunnel is sited within limestone and dolomite formations, considered to be generally competent, and with a range of rock strength considered low to medium as far as TBM practice is concerned (69 to 157 MPa). In addition these materials are not abrasive, and disk cutter life is therefore anticipated to be at the high end of the range of historically based life expectancy. The curvature of the tunnels is very slight. The tunneling conditions are therefore considered as excellent. (Harza Engineering Company report on siting the Superconducting Super Collider in Illinois, 1988).

A significant quantity of performance statistics for TBMs operating in very similar conditions is available, providing a solid baseline for projected performance on the booster tunnel. One source for data is the TARP project in Chicago, on which tunnels were excavated through closely related rock formations. A very good performance on that project was achieved by Robbins machine serial number 147-210 in 1979. This machine bored a 14 foot tunnel establishing very high short and long term overall advance rates, when compared with overall TBM averages. It achieved a best hourly advance of 5.4 meters and a best monthly advance of 1340 meters. Of significant interest is the fact that this particular machine was equipped with a cutterhead drive of only approximately half the power and speed that is common at the present time. In 1997, Robbins serial number 171-231 achieved a best monthly advance of 1513 meters on TARP.

Three other recent instances of high performance have been on the Blue Mountains project in Australia with an 11 foot diameter machine, the River Mountain project in California with a 14.25 foot machine, and on the Superconducting Supercollider project in Texas with a 16.4 foot machine. The Blue Mountains tunnel was bored through 50 – 80 MPa sandstone. The best hourly advance was 12 meters and the best monthly advance 1760 meters (Logan, 1993 RETC). The River Mountains machine reached a penetration rate of 10.7 metre per hour, and had a best monthly advance of 1639 meters (McCormick, 1997 RETC). The Supercollider machine achieved a best month of 1864 meters in 35 – 55 MPa chalk.

It is worthwhile noting that all of the above tunneling systems employed continuous conveyor muck removal. Continuous conveyor systems are described further on. As indicated in Table 3, the Meraaker project in Norway achieved a high monthly rate with a rail system. However, this was at a time when the tunnel length was less than 6 kilometers, where a single locomotive and two muck trains was adequate to match the tunneling rate (Johannessen, 1993 RETC)

Table 3 is a listing of projects on which a high level of performance has been achieved, noting some relevant features of the projects and giving the basic technical specificatons of the TBMs involved.

A realistic target for productivity on the booster tunnel is to make the best recorded performances the average performance, providing this can be achieved at reasonable cost. To guarantee this would require incremental excavation rate improvements such as suggested in section 3.4.1 and operating system efficiency improvements suggested in section 3.4.2. The manpower required need not increase with higher advance rates, and the overall effect of higher speed is to reduce the total labor costs.

3.3 TBM Tunneling Cost Factors

The overall cost of tunnel construction is based on the following items:

(a) The costs (including interest expense) of owning or leasing capital equipment.

(b) The material costs of operating the equipment including replacement of consumable items and spare parts.

(c) The costs of material placed and left in the tunnel.

(d) The costs of power and water supply.

(e) Direct and overhead labor.

(f) The costs of setting up and dismantling the tunneling system.

(g) The costs of disposal of the excavated rock.

This review is confined to the actual construction of the main tunnel itself, and not of the access shafts or adits; or the cost of setting up the tunneling construction supporting site. Figure 1 is a pie chart indicating the current general distribution of tunneling costs.

Capital Equipment:

The prices of new tunnel boring machines have dropped over the last ten years, owing to an oversupply of manufacturing capacity relative to a limited demand, and competition from used machines. Before they are reused, the machines usually need extensive refurbishment and some structural modification for the new task, and usually cost of the order of 70 percent of an equivalent brand new unit. The second hand value of a new machine after average use is about 25 percent of its original price. The purchase of a new machine should guarantee the inclusion of the latest available technology, and that the machine is matched to the anticipated tunneling conditions, and these factors can be significant for a long tunnel.

Behind the tunneling machine an extensive support system, known either as the back-up system or "trailing gear", is required. This includes means of moving the excavated muck from the rear of the machine, power transformers and electrical switchgear, ventilation and dust control equipment, equipment to handle tunnel lining or support material, such as pre-cast concrete segments, rock bolts, or sprayed shotcrete.

Rock drills and tunnel support erection equipment may be fitted on the machine as ancillary equipment. The drills can be anchored relative to the stationary grippers during the boring stroke, permitting simultaneous boring and rock drilling, providing there are no excessive steering motions and the operations are coordinated. This permits virtually immediate roof support. In general, immediate ground support will not be necessary, but a regular rock bolting program may be required to ensure long term safety. In this case, drilling equipment may be more conveniently located on, or even behind the back-up system where conflicts with the TBM operation are reduced.

The trailing gear structure usually rolls along a rail track, which is extended in sections as the tunnel advances. The power supply cabling, water supply and drainage piping, and ventilation ducting have also to be extended. Mechanical equipment to facilitate these operations is usually mounted on the trailing gear. Improvements in the techniques of facilities extension have been made over the years, but it still remains a labor intensive operation.

The muck is carried out of the tunnel either on rail mounted muck cars or by an extending conveyor system. Besides carrying the muck out of the tunnel, transport is also required for bringing in supplies and personnel. Supplies include rail, invert segments if used, utilities such as ventilation ducting, electric cable, and water pipe, and tunnel support equipment such as rock bolts, arches, and cement. The rolling stock is normally part of the muck train. In a long tunnel, when using muck cars, a large number of trains is required to keep up with the advancing machine, and provisions must be made for trains to pass each other in the tunnel. In small tunnels (less than 15 feet or so), it is not possible to use a double track system, and special passing sections (California switches) are used. If the synchronizing of the trains is not conducted efficiently, delays in the train arrivals occur, forcing the TBM to halt operations.

So-called continuous conveyors provide a very efficient alternative to muck trains. They are available at all times during the boring operation, and despite having a high capacity occupy a small portion of the tunnel cross section. The extension of the conveyor is mechanized but usually needs two men to support the operation, one to install the wall or roof conveyor idler mounting structure after the TBM has passed, and one to position the conveyor frames on the supports at the installation station on the back-up..

Although a continuous conveyor eliminates the need for muck cars, a train is needed to haul in material supplies and personnel. However, the number of journeys is lowered and train passing facilities should be unnecessary. The number of locomotives, usually diesel powered, is reduced. Battery operated locomotives are a possible option. As an alternative to rail, the application of a rubber tired system can be investigated.

The capital cost of continuous conveyor systems is high, and the costs should be compared with rail mucking before a selection decision is made, taking into account the improved efficiency.

The costs of supplying rail track must be included as a capital expense.

A breakdown of major capital cost items is given in Table 4.

duty they are, as the internal stress levels will be reduced with increasing component size. Larger size cutters can more readily absorb the impact energy developed during the irregular action of rock cutting. In addition contact stress effects reduce as rolling bearing component radius increases.

The history of cutter development has shown that gradually increasing cutter size (11 inches in the earliest machines), has resulted in an overall increase in TBM performance and reliability. That the 19 inch cutter has met with very limited acceptance owing to its bulk, indicates that 17 inch cutters represent the ideal, which is why they have become the standard, with a large number of competing suppliers ensuring minimum costs and adequate supplies.

If adequate penetration can be achieved with a smaller cutter, however, the cutterhead thrust loading is reduced. This would reduce the TBM capital cost somewhat, as a lower rated main bearing, and smaller gripper and thrust cylinders could be used. However the resale value of the TBM would be impacted if it did not meet the 17 inch standard.

On the 8 foot cutterhead, a 15.5 inch disk may be used to allow more space. This disk uses the same bearing as the 17 inch cutter.

Figure 4 shows a cross-section through a typical disk cutter.

3.4.1.3 Cutterhead Speed

TBM cutterhead speed is normally limited such that the peripheral (gage cutter) speed does not exceed about 160 metres per minute, although speeds up to 180 metres per minute have been used. There is no particular theoretical basis for this limit in terms of the cutting action itself, although the imposed centripetal accelerations may prevent the material scooped up by the muck buckets from falling onto the conveyor belt above critical speeds. This effect is inversely proportional to the diameter at a fixed peripheral speed, and so is more critical on smaller machines.

As the cutterhead speed increases, vibration and impact loading becomes more severe, and the cutter disks are required to run faster, subjecting the roller bearings to heavier duty. As the cutter disks will be working harder, they will run hotter. None of these factors has yet been quantified in terms of shortening component life. In an industry where reliability is a major consideration, and current TBM advance rates are considered acceptable, there is no particular incentive to experiment with higher speeds.

Until comparatively recently cutterheads were normally driven by fixed speed electric induction motors. The ability to vary speed to match ground conditions has always been desirable, but the best that could be done was to use electric motors with two fixed speeds, or inefficient hydraulic drives. Because of the operating environment, DC motors are not suitable for TBM use, and so while variable speed DC drives were available, they were never a practical option. The improving power range and reliability of variable frequency electric (VF) drives has now led to their reliable application on TBMs. Current design practice limits the maximum cutterhead speed to the normal values, but the new drives offer a simple way of experimentally extending the speed range in the pursuit of better performance. Sufficient power must be available to benefit from the maximum possible penetration. The apparently benign conditions on the booster tunnel would serve as an excellent test case, as orientation to high end performance rather than the ability to negotiate poor conditions is justified.

Some TBM manufacturers have traditionally used hydraulic drives (for example, Lovat, Herrenknecht, and Wirth), usually to provide speed variation. The average efficiency of these drives is of the order of 66 percent, which allows for friction and leakage in the pumps and motors, and for losses in the control valves and plumbing. The inefficiency appears in the form of heat, and additional cooling means are thus required. One claimed advantage of hydraulic systems is that they are easier to understand and troubleshoot than electrical systems, as they are essentially mechanical. On the other hand the electrical system, with fewer moving parts is inherently longer lasting and reliable. As the booster tunnel system is likely to incorporate a large number of electronically based systems, skilled personnel will be available for VF maintenance.

Table 11 is a comparison of cutterhead drive options.

Table 12 indicates a proposed specification for a TBM suitable for high speed excavtion of the booster tunnel, and Table 13 shows its estimated instantaneous penetration rate in the range of rock conditions anticipated.

3.4.1.4 Internal Mucking Systems

If the instantaneous advance rate can be improved by increasing penetration, cutterhead speed, or by a combination of both, then handling of the increased material throughput must be assured.

The first stage of handling is the pick up of excavated material as it falls from the face. The majority of material is scooped from the invert by peripheral buckets, although radial buckets can be incorporated in the cutterhead face to catch a portion of the material. A further potential advantage in reducing the number of cutters would be to use the extra available space to increase bucket capacity. As far as speed increase alone is concerned, the situation is self-regulating as the amount of material per revolution is unchanged. The buckets must be designed with adequate scooping capacity, and with internal throat clearances wide enough not to choke the flow as it discharges from the bucket near the high point of the cutterhead revolution. The booster tunnel material is expected to be generally hard and dry, so that clogging of the buckets is not expected to be a significant problem.

The material is dumped from the buckets via a hopper onto a conveyor belt running the length of the machine. The belt size and speed must be chosen so that the muck piles deposited by the buckets are contained within the belt width and do not interfere with any of the TBM structure during their passage through the machine. At the rear of the machine the material is transferred to another belt and ultimately to the main tunnel muck handling system, whether train or continuous conveyor. Because the tunnel materials are non-abrasive and non-adhesive, the belt is not subject to high wear or demanding cleaning requirements. These factors may allow higher than normal speed, offsetting the need for greater width.

3.4.2 Operating Efficiency Improvements

Maximizing the overall advance rate of a tunneling system is dependent not only on the boring speed that can be achieved, but also on minimizing the time that the system is not operating (downtime). The efficiency of the system is usually measured by the "Utilization Factor". The Utilization Factor can be defined as the percentage of the total shift working (including maintenance and repair) time that is devoted to boring. Non-working weekend days and holidays are not included. In references to tunnel boring efficiency in the general literature, the term may be defined differently, so it is important to find out in any particular case what the definition used is. A related term is "Availability", which is applied specifically to mechanical equipment and expresses its efficiency as an independent unit, standing alone from the other operations in the tunnel. Availability has a direct bearing on utilization.

Figure 5 is a pie-chart showing a typical breakdown of the times spent on various activities during a tunneling operation in competent ground. A chart depicting operation in poor ground could include time lost due to rock support.

Current utilization factors are of the order of 25 to 50 percent, so it appears that much scope is available for improvement. One aspect of this statistical term that should be recognized, however, is that for a constant amount of downtime, improvement in penetration rate leads mathematically to a decrease in utilization (as boring time is reduced). In fact however the net daily advance is greater, which is the desired result. This is illustrated by Figure 6.

Factors which currently contribute to downtime, and which can be quantified to some extent based on experience, are: regripping the TBM at the end of the boring stroke, changing cutters, installing pre-manufactured floor segments (if required), advancing the track, and the electrical, ventilation, and water supplies, surveying tasks, and regularly scheduled maintenance. Factors which are not predictable include major equipment repair requirements, installation of temporary rock support, major geological problems, supply system breakdowns, and short or long term unavailability of labor.

With careful planning, some non-boring activities can be worked on simultaneously, so that actual down time is less than the sum of the parts. For example cutter changing would normally done during a maintenance shift. It should be possible to schedule surveying tasks and utilities advance during this period as well.

These elements will be reviewed in some detail, starting with those directly involved with machine availability. As indicated in the text, cutter life and changing time will be minor factors in overall utilization on the booster tunnel, but a review of the potential improvement is included for the sake of completeness and for future reference.

Tables 16 and 17 show the estimated increase in utilization resulting from individual improvements discussed below, where considered applicable. Table 16 shows the cumulative increase, while Table 17 indicates the individual contribution of each improvement.

3.4.2.1 Cutter Life Improvement

Over the 40 years that hard rock machine tunnel boring has been successfully applied, a great deal of research has been conducted on cutter technology. The main elements are the disk materials and heat treatment processes, the disk shape, the roller bearings, and the lubrication and sealing system. The modern cutter is mechanically very reliable with the disk material the limiting factor on life. The life of the bearings is independent of the life of the disk, on which wear is dependent directly on the abrasive content of the rock. The bearings will usually outlast the disk even in the least abrasive conditions.

Figure 7 shows typical cutter ring cross-sections that have been developed. The preferred type is the so-called constant section ring. As it wears, the tip width does not increase significantly, and there may be some self-sharpening effect. The cutter force – penetration relationship is therefore more or less constant. The wedge shaped cutter is primarily designed for impact resistance in very hard and fractured rock. The constant section rings are appropriate for dolomite and limestone.

It is impossible to predict when, and by how much, materials will be improved in the future, and for the purposes of this study it is advisable to assume that no particular improvement will occur before the booster tunnel is constructed. In any case, the prevailing rock has very low abrasivity, and historical records indicate that in similar conditions, each cutter disk, on average, can excavate around 1000 cubic metres before needing replacement. This is equivalent to a tunneling distance of approximately 3000 metres, and therefore the impact of cutter consumption on overall cost and tunneling duration is negligible.

A secondary, although important , influence on cutter wear is the grouping of the cutters in certain critical areas. This aspect has been covered in the discussion on cutter spacing contained in section 3.4.1.1.

3.4.2.2 Cutter Change Techniques

Cutter assemblies are very heavy, awkward to handle, and generally located where access is difficult. Cutter handling is a lot easier when done in front of the cutterhead than from behind, as access is not impeded. If rock conditions are safe, then the front change approach is recommended. Cutterheads can be designed to be accessed from the front or back only, or can be designed to be accessed from both sides. The gage cutters are a special case, as the tunnel wall prevents than from being removed radially outwards for removal, and if changing from the front is required, they must be mounted on two piece pedestals which allow forward movement.

The standard wedge type mountings require only two bolts to lock the assembly in position. A mechanical tool is available to hold the assembly as it is removed from its seat. A hoisting system (usually air powered) is used to lower or raise the assemblies to or from the cutterhead support access area.

It is best to change as many cutters as possible during any one session. Cutters do not wear uniformly and it is not normally possible to change a complete dress at the same time. However, efficient planning of the changing procedure can save time. Available records indicate that the whole operation averages about 45 minutes per cutter.

Potential improvements in cutter change time can come from designs that are easier to change. Standard cutters are mounted on a double-ended shaft, and the complete assembly has to be removed in order to change the one-piece rings. The use of cantilever mounted cutters would theoretically make cutter changing easier, as the ring can be pulled directly from the hub. In practice however, the rings must be tightly secured on the hub with a shrink or press fit, or they will work loose, rotate relative to the hub, and be destroyed. Various proposals to overcome this objection have been suggested such as a tapered seat. Another problem is that the cantilevered shaft may not be able to withstand the violent loading experienced by the cutter, and a bending load is imposed on the cutterhead structure. Experience has shown that the dynamic stresses imposed by the cutting action are extremely severe, and load paths should be designed as conservatively as possible.

Another proposed solution to facilitate disk changing is a multi-section disk which fits around the hub, but the difficulty of locking the sections securely against large dynamic loads has indicated that this is not a practical option.

Another option is the application of robotic systems to cutter handling. This is very difficult given the number of different cutter locations that exist and that any tool would almost certainly need to be removed while the TBM is operating.

Given the long cutter wear life anticipated on the subject project, and that improvement of current change procedures is uncertain and will be expensive, it is concluded that this is not a worthwhile area for immediate investigation.

3.4.2.3 Regrip Time Reduction

At the end of every boring stroke, the wall gripper shoe mechanism must be recycled forward. On an open type TBM, this involves setting down temporary support legs so that the weight of the machine can be removed from the grippers, and raising them clear of any obstruction before the next stroke commences. The overall cycle time is of the order of four minutes. As well as resetting the gripper, the alignment of the machine may need adjustment to ensure that it is boring in the required direction.

Decrease in regrip time can be accomplished in a number of ways. The most dramatic is to use a double gripper system, where one unit is cycled forward as the other thrusts the machine, effectively eliminating regrip time loss. This concept was designed into the "triple-shield" TBM used on the Texas based Supercollider project. In practice the system proved too complicated and unreliable, and the machine was converted to a standard double shield arrangement with a single gripper set. However, it may be that had more time been given to improving the system, it could have worked satisfactorily. One problem hindering advances in the tunnel boring industry is the desire to move the tunnel ahead, rather than spend time researching improvements. The reason is that the contractor usually is more interested in completing the task for which he is getting paid for, rather than in product improvement. However, the addition of a second gripper and propel assembly and a synchronizing control system would be very complicated and expensive, and the costs might far exceed the benefits of the time saved. A thorough examination of the potential for incorporation of a continuous system, which necessitates an intensive design study, could be the subject of the next phase of this study

Simply speeding up the operation, if practicable, will reduce regrip time. The motions are powered hydraulically, so increasing the rate of movement is basically a matter of more installed power and adequate line and porting sizes. Safety can be jeopardized by rapidly moving structures and should be taken into consideration. The Robbins 171-231 machine used on the 79th Street TARP tunnel was retrofitted with a high speed resetting system, with a hydraulic cycle time of 75 seconds, and the River Mountains machine was similarly modified, with a reported 45 second reset. Resetting time is involved solely with actuator motion, and does not take into account other contributions to the overall regrip cycle time. It has to be remembered however that during the operation the machine is likely to move out of its correct alignment, and some adjustments usually are needed, adding to the theoretical cycle time. These adjustments are currently made by the operator, and could be automated.

Another way to diminish the impact of regrip is by increasing the boring stroke. This is normally standardized at about 1.8 meters, but could probably be almost doubled. This would decrease the overall time on a 17000 meter length by 19 days. On the application under review the tunnel curvature is very slight, and there would be no wall interference problems using a longer machine. Practical issues to examine are the possible need to increase thrust cylinder size to avoid buckling, and the impact on machine length, however the costs of such a simple design modification should be reasonable.

Table 14 presents a step by step analysis of the entire gripping cycle, and indicates attainable targets for reducing regrip cycle time.

3.4.2.4 Logistics Improvement

It appears that on this project the overall tunneling system advance rate can be substantially increased (say 25 percent) over those currently accepted. Conventionally, potential instantaneous advance rates in excess of 6 meters per hour (100 mm per minute) are disregarded as being unsupportable. Matching that pace with the remainder of the system is perceived as a problem, and current acceptance of the myriad practical problems that arise, appears to prove the point. There is a degree of comfort in this approach, and it seems to be generally accepted by those involved in tunnel construction. Competition between contractors is usually based on component pricing, more than on speed based on technical improvement, and the schedules imposed by the owner are generally not technically demanding. For short tunnel construction, which does not dominate the critical path of the overall project, speed is not important. However, a long tunnel is where the possibilities of increased rate should be closely studied. A good example is the Channel Tunnel where high advance rates of up to 1400 meters per month were demanded, and achieved. A tunnel constructed 20 or so years later should be built even more quickly.

The critical TBM support systems are those concerned with carrying the muck out of the tunnel, and those involved with keeping it moving forward at a speed at least equal to the net excavation rate, allowing for regrip. The latter are those advancing the track or roadbed on which the trailing gear runs and extending the electric power, water, compressed air, and ventilation services.

An interesting tunneling system used on an 8.5 foot sewer tunnel in Chicago is described by O'Connor in the 1985 RETC Proceedings. While the methods described are not directly applicable to the booster tunnel, it shows appropriately engineered support systems can lead to very efficient production.

3.4.2.4.1 Tunnel Mucking Systems

Muck Train

The principal system in use today for carrying out tunnel muck is a train of rail-mounted cars hauled by diesel powered locomotives. The system is reasonably efficient overall, although problems occur in long narrow tunnels where it is necessary to use a sizeable number of trains in order to keep up with the muck production, which must pass each other in the tunnel at special double track sections. In any long tunnel a rail system is the most efficient method of hauling in supplies and personnel, and therefore a track is necessary, whether or not it is used for muck transport. The heavy muck cars may require larger section track. A rail system used for muck hauling will require a greater number of, and more highly powered, locomotives.

The cars are loaded from an overhead conveyor system. In some cases the train is loaded by moving it below a fixed dumping point, and in others the train is stationary while the conveyor discharge point is moved. Both systems require co-ordination of the filling process to avoid under- or over-loading, as the muck distribution along the belt is not generally uniform, and the bulking characteristics of the broken rock may vary. The arrival and departure of the trains must be coordinated with the TBM cycle to avoid idling the machine unnecessarily. Supplies for forward advance such as segments and track are brought in with the muck train, and again coordination is required to assure efficient transfer of these items without impinging on the mucking cycle. A number of elaborate schemes of train handling involving twin track back-up systems have been employed to improve this process, but these are difficult to install in a narrow tunnel.

The cars are usually unloaded automatically, either by the use of floor dumping or tipping.

Factors contributing to the costs of muck train operation are the capital costs of the rolling stock, the special loading equipment required on the back-up system and at the portal, the track (which may be required for other reasons and therefore not directly chargeable), the fuel costs, and the costs of the locomotive drivers and loading supervisors. Additionally, the costs of maintenance, spares, and repairs must be included.

A further factor may be any additional ventilation requirements imposed by the intensive use of diesel locomotives. This includes aspiration requirements as well as assuring adequate exhaust dilution.

There is an active secondhand market in rolling stock, which offsets those specific capital costs.

Continuous Conveyors

The use of the continuous conveyor system is spreading rapidly in tunnel construction. The majority of the tunnels cited in Table 3 used them, for lengths up to 13.4 kilometres. It is a well proven and reliable method. It is a non-cyclic, simple, and efficient. The loading point of the conveyor is located on the trailing gear close behind the TBM. As the system advances the belt is pulled forward. The belt supporting idlers are permanently installed and anchored to the tunnel wall from a work station behind the tail pulley. In small diameter tunnels the conveyor system is occasionally suspended from the roof, if there is inadequate clearance at the sidewall. If continuous rock bolting required, it may be possible to use the bolts for supporting the idlers. The total length of the belt back to the discharge point at the portal must increase as the system moves forward, and this accommodated by a take up unit, located at the portal. After a certain length of advance, a new piece of belting is threaded into the take up unit, so that the belt can be extended virtually indefinitely. Intermediate booster drives are required for very long distances, as belt tension and drive power would become excessive with only one unit.

Because it is dedicated to mucking and is non-cyclic, it is virtually always available when the TBM is ready to bore. Regular maintenance work can be scheduled at the time that new belt sections or booster drives are installed, to reduce lost operating time.

Hauling in supplies and personnel is therefore de-coupled from the far more intensive mucking requirement, which greatly improves the efficiency of both operations.

Manpower requirements are low. One operator can install the idlers, and at the same time monitor the belt loading as the muck is transferred from the TBM system. An additional worker is needed to install the idler supporting structure to the tunnel wall. It may be possible to automate the installation system, although the manufacturers have not identified this as a current priority, because of the complexity of establishing a viable solution./A crew is needed to load in the new belt and install the booster drives.

The continuous conveyor system appears to be an ideal application for this project. The curvature is negligible, and the materials are generally not expected to be abrasive or sticky. It is difficult to train belts around curves, and the curvature decreases the fatigue life of the belt. Dry and easy flowing materials do not need the extensive mechanical belt cleaning measures that abrade the belt and shorten its life.

The main contributions to cost, apart from manpower, are the belt itself, the drives, the take up unit, and the idlers. Energy costs are lower with electric drives than with diesel powered locomotives, but the cost of the cabling must be taken into account. The drives and take up unit have good resale value at the end of construction, but the residual value of the belt and idlers may be low as they will experience substantial wear.

The major problems that have been reported on continuous conveyor systems have to do with synchronizing the intermediate booster drives that are necessary on very long tunnels, particularly at start up. It has to be assumed that these problems which are basically those of a group dynamic control system will be solved in the near future will be solved by improved feedback and processing techniques.

Figure 8 shows a complete small diameter back-up system for use with a continuous conveyor system. Figure 9 shows cross sections for tunnels over the diameter range under consideration and the space required for rail and conveyor systems, and for ventilation. These are the major items competing for space.

Other Wheeled Vehicle Mucking Schemes

In large section, short tunnels with flat floors, diesel powered rubber tired dump trucks are used. They are not suited for the cramped conditions in long narrow tunnels. Single truck operation is highly labor intensive, and multiple trailer units are impractical in such conditions. In small diameter tunnels it is essential to have the positive guidance of some kind to prevent collisions with vehicles coming from the opposite direction. Usually a rail system is used, but rubber tired vehicles running in grooves integral with invert segments can be considered.

Pipelines

Pipelines are used to carry materials in slurry form. Commonly used in conjunction with soft ground slurry type TBMs, they are rarely used in hard rock tunneling. One reason for its application would be if there is considerable water inflow into the tunnel and the material is already wet, and therefore messy when loaded on conveyors or in muck cars.

A pipeline system requires specialized slurry pumps (including multiple booster units on a long installation) equipped with speed controls to balance pressure losses and flow rates, and separation and filtration plants so that the water can be reused without silting up the system. Telescopic units fitted with shut off valves to prevent spillage are used to extend the system. Additional sections of pipe are added when the telescopic section reaches its full stroke.

Pipeline systems are more suited for permanent long distance material handling installations, for example coal transport, where conditions are less variable, and the high capital costs can be amortized over a very long period. In addition, slurry transportation of solids is not an energy efficient process.

3.4.2.4.2 System Advance

Rail or Roadway

Means of supporting and guiding the trailing gear and the supply vehicles (and mucking vehicles, if used), must be installed behind the tunneling machine. A number of alternative arrangements have been used. It is generally not acceptable to attempt to run the equipment on the bare tunnel floor. Although in competent ground the boring action generally produces a very smooth finish, there will inevitably be lengthy sections where the surface is pitted and rough which may cause wheel jamming resulting in forcing the equipment out of alignment. Trailing gantries are not necessarily wheel-mounted; on some systems they are supported on skids, but these applications are usually associated with pre-cast segments.

The simplest arrangement is where the trailing gear runs along the same track used for the supply and muck trains. The rails are installed as close as possible behind the TBM, but it is usually necessary to support the front end of the trailing gear independently of the track, so that it can be laid in reasonably long sections. The track is laid on ties which conform to the tunnel floor. Ideally the ties are secured to prevent lateral movement.

A better base is provided by the installation of pre-fabricated floor segments, usually concrete. These can serve as a permanent floor after completion of the tunnel, if one is needed. Internal passages in the segments can be used for temporary or permanent utility installation. Rail fixture attachments can be built in. For very long tunnels, it may well be worth investing in complex segments, as the benefits of mass production will lower costs. Conceivably short rail sections could be pre-assembled to each piece, although normal practice is to use intall rail lengths of up to 30 feet. This has the advantage of reducing the number of rail joints. The segments are normally not in direct contact with the tunnel floor, but sit on a gravel bed, which may be grouted to guarantee stability. The bed accommodates any undulations and variations in the bore diameter due to cutter wear in the tunnel. For trains running at fairly high speeds (25 kmh), it is important that the rail track is correctly aligned.

The circular bore produced by a full face TBM is a disadvantage if a flat floor is ultimately required. Concepts have been developed for secondary corner cutting machines attached, or close, to the rear end of the TBM which can produce a flat floor, but none are believed to have reached the production stage. A machine with a drum type cutterhead equipped with disc cutters appears to be the best solution. The main problems are controlling the floor geometry, providing reaction paths for the cutter forces, muck collection, and dust control. The scope of the present study does not allow for an in-depth investigation, but give the overall tunnel length, a design study could be justified.

Figure 10 shows a comparison of the useful areas of circular section and "horseshoe" shaped tunnels.

Ventilation System Advance

There are three main considerations in controlling air quality in hard rock tunnels; provision of adequate fresh air for respiration and diesel aspiration, dilution and dispersal of diesel fumes, and the elimination of the large quantities of dust generated which escapes damping by water spray. The dust control equipment is self-contained within the TBM and trailing gear section. Airborne dust is sucked through a scrubber unit and filtered out.

Fresh air is provided in one of two ways: by blowing fresh air in through ducting, or exhausting the air through ducting, and inducing fresh air flow inward from the access shaft. One advantage of the former method is that the ducting is always subjected to an internal positive pressure and so flexible, thin-walled collapsible ducting can be used. This has enabled the use of the very efficient duct storage system for extension of the ducting. A length of ducting (up to 200 metres) is stowed in concertina fashion in a metal can, or cassette, which is mounted at the rear of the trailing gear. The ducting automatically paid out as the system moves forward, and suspended (manually) from a pre-installed wire hanging from the roof. When the cassette is almost empty, it is exchanged for a full one.

The exhausting (negative pressure) type system requires the use of stronger, reinforced ducting, and a rigid telescoping section is used to accommodate system movement of up to 10 metres. New sections of duct are added when the full extension is reached. This system is obviously not as efficient as the use of the cassette.

In long tunnels, booster fans must be installed at intervals, to overcome the pressure losses along the ducting.

Electric Power

Electric power is delivered to the tunneling system at as high a voltage as is practical, to reduce current, and therefore cable size. Voltage loss along the cable must be held to an acceptable minimum. The maximum voltage normally used is 25 kV. In order to extend the cabling, a cable reel is generally used, with as much as 300 metres of storage capacity for special flexible trailing cable. A new length of permanent cable is added when the trailing cable is fully paid out, after which it is rewound. As tunnel size gets smaller, the cable reel is more difficult to accommodate, and in some installations, instead of a reel, cable is spread in a multiple loop along the trailing gear and gradually paid out. The delivery of the new length of cable and its installation along the tunnel, or into the cable tray should be scheduled during maintenance periods to avoid loss of boring time.

A possible alternative is to tow the cable into the tunnel on some sort of carrying system, such as a low friction monorail. A stationary large capacity reel would pay out the cable. Some intermediate traction sources would be needed along the long tunnel, but the fact that the tunnel is virtually straight is very helpful. In addition water pipe and other utilities could be extended using the same carrier. This would eliminate the problems of in-tunnel extension of services, and result in increasing utilization , but with a penalty in capital cost.

If the voltage drop along the cable is excessive, booster transformers will be required at intervals. This would preclude the towed cable scheme, as the transformers would have to be located in specially excavated alcoves along the tunnel. By towing however, a considerably larger section cable could be installed than is possible with the more flexible small cross-section cable necessary for handling within the tunnel. There would be a trade off between cable cost and booster transformer cost.

A great length of expensive power cable is required, plus a large number of expensive connectors. The installed cable may have a use in the completed facility, which would offset the construction related cost.

Alternative power sources can be considered, but they have serious disadvantages in comparison with basic 3-phase power delivered from the electric grid.

A very large diesel generating plant would be required in order to meet the power demand of even an average performing TBM. One problem of a dedicated plant is that its capacity must be large enough to supply temporary demand overload, which may be more than twice the normal output. The power grid is easily able to supply this, as the TBM demand is a small percentage of its total capacity, assuming that the branch circuit transformers and switchgear are adequately sized. The aspirating air and exhaust dispersion requirements far exceed normal ventilation needs, a vast amount of waste heat is generated, and adequate noise attenuation in the tunnel confines may be impossible. Apart from this the fire danger is dramatically increased.

It may be feasible, by substantially reducing the TBM power demand, to limit such an alternative power source to a practically supportable size. However the net cost of loss in performance, due to slower construction, would probably more than offset any benefits gained. In any case, as the power requirements diminish, the cost of the electrical supply system would reduce proportionately.

This is a preliminary view, and a fuller investigation may be justified in order to come up with true costs and technical requirements.

Water Supplies

Water is required for cooling electrical and hydraulic components, damping down dust, rock drill flushing, shotcrete mixing, and general equipment wash down. The service is extended by using a large capacity hose reel, and installing lengths of permanent piping as the hose is extended.

Compressed Air Supply

This can be used in conjunction with rock drilling, shotcrete application, and for hand tools. On a long tunnel, a portable air compressor is normally carried on the trailing gear, rather than extending a pipeline from the portal. If a pipeline is used, it will be extended with a hose reel in a similar manner to the water supply.

Drainage

There is normally some water inflow into the tunnel that must be drained away. If the tunnel is bored uphill, the water can be drained under gravity. Depending on the existence and shape of an invert segment, it may be guided along an integral channel.

When boring downhill, waste water must be pumped out of the tunnel. The set up of the piping system and extension facilities are the same as for the incoming water supply.

When possible, boring should be arranged to go uphill. This will probably not be practical on all the segments of the circular booster tunnel.

3.4.2.5 System Reliability Improvement

A major cause of lost time in the tunneling operation is due to equipment malfunction and breakdown. There are a number of reasons for a high incidence of equipment failure.

Custom Design: The number of tunnels bored by TBMs is relatively few, and very rarely are any two alike, in size, type, geology, location, or contractor practice. The number of machines in existence is very small compared with the population of other heavy construction equipment, for example bulldozers, and so experience, particularly of component reliability, is not gained as rapidly. The design criteria for machines vary widely, and each new machine is to some extent a prototype. New design features or alternative components may be introduced with the intention of improving reliability or serviceability, but these frequently require modification to rectify unforeseen faults. It is not possible to simulate boring conditions at the manufacturing plant, and therefore it is impractical to attempt full load testing of new equipment before it is put into use. However, the overall reliability of TBMs is such that TBM use is viable.

Geology: Geology has a major bearing on the way that the machine and the rock interact, and equipment that has performed very well on one job may encounter problems in ground with different characteristics. Drive systems may become overloaded because of high resistance to cutterhead rotation, mucking systems may become clogged with sticky materials, and high levels of destructive vibration may be experienced in hard and blocky ground.

Major geological problems such as roof instability or faults can slow or stop the operation, but these are not considered to be a reliability issue.

Tunnel Environment: Rock falls and water may damage equipment and track. Limited space and restricted vision can result in material or equipment obstructing movement and causing damage. Warning signs of component failure may be overlooked because difficulties of access deter adequate inspection.

Means of improving overall reliability, with relevance to the booster tunnel, are reviewed below.

A listing of the most common reasons for breakdown of a TBM system, indicating the corrective actions and approximate repair times is given in Table 15.

3.4.2.5.1 Design and Manufacturing Quality

Despite the comments made above regarding the problems inherent in designing equipment for custom use, a substantial body of proven design criteria exists, based on field experience, which provides a sound basis for determining the overall machine configuration.

In order to procure the best possible product, the customer should take an active role in the machine design and manufacturing process. He should provide input on the proposed overall plan of construction and monitor progress. Good design requires attention to detail, which in turn requires an adequate time allowance. Frequently, because of cost and scheduling pressures, adequate time is not provided, and the design suffers.

Useful analytical tools which aid in structural design, such as finite element analysis software which can be related directly to computer based drawings via solid modeling (e.g. "Solid Works"), can be now be made available at the design engineer's workstation.

As stated above, testing under actual tunneling conditions is not practical, however functional testing should be performed at the manufacturing facility. This should include exercises in cutter changing, and the deployment of ancillary equipment such as rock drills.

3.4.2.5.2 Planned Maintenance and Spares Availability

Because of the generally adverse underground environment, regular inspection and maintenance of the equipment is a necessity. This includes daily inspection of the cutters, muck buckets, and the conveyors, greasing of moving parts, and frequent monitoring of the condition of hydraulic and lubricating fluids. A minimum acceptable maintenance program will be specified by the manufacturer.

The timing of maintenance depends on the contractors overall schedule, the labor available, and the work load. It may depend on local labor practices, whether there are restrictions on surface transportation muck haulage, and on how many actual working days per week are planned.

A good selection of spares must be always kept available. It is impossible to predict spares usage, apart from regularly used items such as fluid filters, so there usually has to be a compromise between the amount invested in spares and the cost of unanticipated downtime. Major spares, such as cutterhead bearings and drive gears, pose a particular problem. As far as possible, major components should be standardized, and available within a reasonable time. In the event of a major breakdown, it usually will take a matter of days or more to prepare the work area and disassemble the damaged components, so on-site stocking is not necessary.

The removal from the tunnel of major TBM components for repair is very difficult. They must be transported from the TBM to the backup area via a temporary crane or winch system, probably attached to the tunnel roof by rock bolts. They must then be loaded on rail cars. The ventilation line may be an obstruction. Backing up of the trailing gear is a very difficult operation; it is too heavy to haul by locomotive, and all the connections between it and the TBM would have to broken. It would be obstructed by the ventilation line. Ready removal of the TBM as a nearly complete assembly would be even more difficult, considering the difficulty of hauling it, and of coping with the obstruction imposed by the invert segments, if used, and the ventilation line.

The need for major repair on this project is extremely unlikely. The longest drive is 17 km, assuming only two access shafts, and the chances of a major repair being needed are low enough so as not to warrant a complicated design solely based on making repair easier.

In the diameter range under consideration, the cutterhead bearing is in the medium, popular, size range, and while it would not be considered a "fast moving" item, it would probably be available fairly readily. In addition, the geology is expected to be benign. Cutterhead loadings should not be severe, and as the rock is non-abrasive, bearing contamination due to seal failure is a remote possibility.

By using a TBM standard large section bearing, it is calculated that its lifetime under the loadings expected on the booster tunnel will exceed 50,000 hours, equivalent to 500 km at 10 meters per hour instantaneous penetration rate. This provides a very large factor of safety, and should virtually guarantee that the bearing will not be worn out or suffer mechanical damage.

Figure 11 shows a typical cross section through a "3-axis" bearing, which is the preferred style for longevity.

3.4.2.5.3 Electronic System Monitoring

Electronic monitoring of the main machine functions is commonly incorporated on TBM systems, including items such as cutterhead rpm, drive motor currents, propel cylinder pressures. Secondary parameters which should be in a prescribed operating range, such as oil temperatures and reservoir levels are also monitored. In addition, video cameras are used to monitor conveyor discharge points, supply train positioning etc. Data can be extracted from the laser guidance system to determine the machine alignment. The data can be transmitted for real time observation and recording at the surface.

The system can be extended to areas concerned with the mechanical health of the machine, such as detecting abnormal vibration levels at the cutterhead bearing and drive system. Proposals have been made to monitor disk cutter condition, for instance by measuring its rotation speed compared with the cutterhead speed. Any relative speed increase should indicate loss of radius due to wear. Cutter action is spasmodic however, as the rock does not break uniformly, and the accuracy of this method will need proving in the field.

Where frequent failures of certain components have been shown as a major contribution to stoppages, application of appropriate monitoring, advising of the need for repair or replacement before catastrophic failure occurs, would obviously be very beneficial.

Table 18 lists some existing and potential parameters, the monitoring of which could produce higher reliability.

3.5 Tunneling Cost Reduction

Cost Analysis

In attempting to significantly reduce overall tunneling costs, the effect of individual improvements, made on their own, should be examined to determine their net effect. This provides a basis for determining what amount of effort is worth putting into the specific potential improvements, in effect to determine the return on investment. This systematic approach to performance or cost improvement is usually known as sensitivity analysis. It is specifically targeted at the booster tunnel project. The parameters reviewed are tunnel size, advance rate, equipment and material costs, and labor cost. A computer-based spreadsheet, which enables various scenarios to be investigated, is included with the report. A description of the spreadsheet and sample print outs are located in the appendix.

3.5.1 Tunnel Size

As tunnel size reduces, the TBM cost decreases. On a weight basis, the reduction is approximately proportional to the square of the diameter, but cost reduction is partially offset because the machine is not any less complex, and very small machines may need special design features because of the lack of space. The power requirements of machines are proportional to the diameter. Because the limiting cutterhead speed is based on peripheral velocity, the smaller machines can have an instantaneous advance rate inversely proportional to their diameter, assuming the same cutter penetration.

The backup cost will reduce by a factor less than proportional to the diameter, as the complexity remains, and construction material costs are not significantly less. Train passing in the tunnel at the small end of the range is difficult, virtually mandating continuous conveyor mucking.

Labor requirements are unlikely to differ across the size range under consideration. The costs of materials left in the tunnel e.g. segments reduce somewhat with size. Power reduction on the smaller sizes will reduce cabling costs along the tunnel, and transformer size. In addition ventilation supply and distribution costs will reduce, at least proportionately to the diameter.

3.5.2 Advance Rate

The main benefits of rapid tunnel construction are the earlier availability of the facility, the reduction in labor costs, and the reduction in the cost of equipment ownership. Power and material supply costs are not affected, although power consumption and the installed electrical capacity is greater at higher excavation rates. Power costs as such are not a dominant factor in tunnel construction.

Higher overall advance rates may result from any combination of the potential improvements covered in section 3.4.

3.5.3 Equipment and Tunnel Material Costs

As indicated earlier, TBM system prices have dropped significantly in recent years. Future declines are unlikely as manufacturers' profit margins are very low, and most of the economies of production have been achieved.

A major decision facing the owner and contractor is whether to use new or refurbished machines. A new machine can more readily incorporate features matched to the specific job, which enable it to perform more quickly and efficiently. These include all the improvements suggested in section 4.1.4. On the other hand it may be more susceptible to problems with new and untested components as indicated in the comments on reliability, although some protection is provided by the manufacturer's warranty. If two machines are required, new machines have the advantage, as spare parts commonality is guaranteed. It is very unlikely that two identical used machines will be available. If more than one contractor is used, each being responsible for his own equipment, then different machines may be acceptable. The conclusion of this study however strongly recommends that the best approach, if time constraints permit, as they currently appear to, is to bore the complete tunnel with one system.

In addition to the basic machine and backup, auxiliary equipment such as rock drills will be needed. The installation of these for efficient usage needs careful attention and usually costs much more than the drills themselves.

The major material cost item left in the tunnel may be the invert segments. As indicated in section 3.4.2.4.2 there may be overall savings if the segments can incorporate facilities which can assist in faster tunneling or be of use in the completed facility.

3.5.4 Labor Costs

Labor costs represent the second biggest contribution to the overall tunnel construction cost after capital equipment, and are therefore a major target for reduction.

It should be noted that in comparison with drill and blast operations, and especially in terms of advance per man-hour, the TBM system is already very efficient.

Scope for Direct·Manpower Reduction and Automation

TBM Operator

The TBM only requires one operator, as all its mechanical functions are easily controllable remotely from a single location. Steering requirements are based on the divergence of the machine from the laser guidance beam. An electronic laser target provides a remote indication of the current direction and attitude of the machine, and gives any requisite steering correction to be made by shifting the axis of the machine relative to the tunnel. or adjusting the side supports behind the cutterhead. Warning devices inform the operator of critical system malfunctions.

At the end of the boring stroke, the operator initiates the regrip cycle. He is responsible for assuring himself that no personnel are trapped by the large moving elements. After regrip is complete and the machine's alignment checked, the cutterhead is restarted, and advanced. Restarting is not a problem where the face is stable and all the muck has been cleared in front, but calls for some skill in cases where the face may collapse, possibly obstructing free movement of the head. In this case reversing the head may be necessary to back away from the obstruction, before trying again to break out.

The operator is expected to understand the main operating features of the machine, and is capable of performing routine maintenance tasks on it.

As the machine functions are already electrically controlled, the basic technical task of implementing long distance remote control from the surface should be straightforward. What would have tc added however are the visual and audible clues that enable the operator to immediately sense problems when he is located on, or close behind the machine on the backup. For example, starting difficulties such as referred to above, rely on a sense of the machine's behavior, and observation of the ground conditions. Mere long distance remote operation may not be worthwhile, as a trained operator is still required. Obviously some paid time is saved as the operator would not need to make the long trip to the face, and the hazards of being underground are avoided.

Full scale automation is an even further step, and successful operation would depend on the automation system's ability to correctly sense and interpret problems. The situation is analogous to the position of the pilot in a modern airplane. The plane can be flown from airport to airport completely automatically, but the pilot is needed for unusual conditions. Unfortunately unusual conditions are common in tunneling, given unanticipated geological accidents, and the susceptibility to breakdown of sophisticated machinery in a hostile environment.

This is not to say that automation should not be given further serious study. Automation of operations in tunneling has been attempted on a limited experimental basis. One example is the automation of the Robbins Mobile Miner in Australia. This system basically allowed the machine to move ahead without operator intervention, by controlling the sequence of the plunge and sweep cutting cycles of the vertically mounted cutter wheel. After the completion of a set of cycles, the machine would move forward on its tracks and commence the cycle set over again. The advance rate was inevitably slow, given the nature of the cutting action, and rock conditions were known to be good for the limited length of the test. The main problems were found to be in durability of the sensing components (Turner, 1993 RETC).

Japanese contractors in Japan have pursued developments in the automation of various tunneling systems, notably in automatic segment erector systems and segment transport systems. Japan is noted for well financed and also government supported contracts which cover the high costs of such development, which is not the case in the USA.

Tunnel Mucking System

Whether using muck cars or a continuous conveyor to haul the muck out of the tunnel, direct intervention is normally required.

As described in section 3.4.2.4.1 there are a number of ways of loading muck trains. Because the delivery belt loading will vary depending on the TBM instantaneous penetration rate, and because the muck has to be evenly distributed along the car to maximize the loading, it is necessary to adjust the relative movement of the car and the belt delivery point. This is relatively easy for a human operator, as it relies directly on observation of the filling rate. The system could probably be automated based on belt weighing technology and video monitoring.

The continuous conveyor system is not concerned with the loading rate, providing it is sized to match the maximum TBM penetration rate. However it must be extended as the system advances. This is currently done manually, as it involves installing a new idler set on to a pre-installed bracket. For this task to be automated, a highly reliable vision based robotic handling system is necessary. There may be alternative ways of installing the idlers which are more suited for automation. Another worker is required to mount the wall bracket ahead of the idler installation station.

System Advance

Placing the track and its support, and installing the utilities along the tunnel are inevitably labor intensive operations, unless they can be further simplified or replaced by sophisticated automatic handling systems. As indicated in section 3.4.2.4.2, devices such as the ventilation duct cassette, and cable and hose payout systems, are commonly used to ensure continuity of supply and reasonably efficient advance. These systems require manual changeover when the storage length is used up. New materials must be moved from a storage area on the backup to their point of use.

All these operations require handling of heavy components, securing them in place, and in most cases making up some form of mechanical, fluid, or electrical joint.

An attractive concept would seem to be to build some of the advancing utilities into the invert segments (excluding electrical, but including rail and water). With a normal length segment this would result in a tremendous number of joints, but it may be possible to devise a procedure for installing long segments, possibly split lengthwise for handling. Tunnel curvature is so small that it does not pose problems. The segments would have to be laid very accurately. The water joints would need reliable high pressure seals. At least some segments would need a water supply outlet. Drainage water is normally conducted via a central open channel, providing boring is uphill.

A study can be made of the potential for mechanizing the segment installation, tracklaying, and permanent utility installation, which all appear to be repetitive tasks. The main problem that must be faced is the difficulty of replacing immediate human reasoning power and dexterity with a mechanized system. A myriad of mostly simple problems occur during underground construction, which would require an extremely elaborate "expert system" to replicate. Tunnel construction by TBM has already evolved into a moving production line, with many similarities to a modern assembly plant. One difference however is that in a sense, the plant building (the tunnel infrastructure) is always under construction.

Locomotive Drivers

The number of locomotive drivers required will increase with tunnel length, and will be significantly reduced if a continuous conveyor system is used. Automatic control of the locomotives would not be difficult to incorporate as a technical matter, but will raise issues of safety and adequate control in unforeseen situations. Local radio remote control of the system, giving the car mucking supervisor control of train positioning, could be beneficial.

Shaft and Surface Crew

The simplest and least labor intensive way of elevating the muck is via a vertical bucket or pocket conveyor. Personnel will be needed to handle incoming supplies onto the rail cars whichever type of mucking system is used. A crane operator will be required, and men to supervise muck storage and transfer, and handle the supplies at the surface facility.

Supply handling at the surface can be optimized by appropriate bundling of the materials for transport. Bundling may be done at the manufacturing plant. Costs of surface workers in any case are lower, because time is not wasted traveling up the tunnel, and the wage levels are not as high. Optimization of the surface operations is not considered to within the scope of this study.

Maintenance and Repair

Some maintenance duties can be performed by the general tunnel crew, such as greasing, conveyor idler replacement etc., although if their numbers are reduced as a result of increased mechanization, they may not be available.

Specialist mechanics, hydraulic experts, and electricians are needed to service and troubleshoot the more complicated equipment. These personnel can be used on both tunneling systems. The more complex and automatic the equipment becomes, the greater demand there will be for such services, at least on a "stand-by" basis.

4. TUNNELING IN UNSTABLE GROUND

In general, ground conditions in the dolomites and limestones along the booster tunnel alignment are expected to be stable, with some occasional moderately fractured and weathered ground where overbreak will occur unless prevented. Figure 12 depicts the range of rock classes anticipated, and indicates the appropriate support methods.

It is estimated that 93 percent of the tunnel is expected to be in classes I or II. As an insurance against roof falls, pattern bolting as indicated, of two bolts for every TBM stroke is recommended. The estimated material cost per meter is about $75.

Of the remaining ground, approximately 6 percent is anticipated to be in class III, requiring the installation of a bolted in place canopy, costing about $130 per meter. In the rare case that class IV ground is met, a canopy supported by full ribbing, estimated at $250 per meter will be needed.

It is vital that the regular rock bolting does not impede the high planned advance rate of the tunneling system. As normally there is no danger of immediate rock fall, the bolt installation can be performed a long way back from the machine, either from the back-up, or from an independent platform behind the back-up. The TBM should however be equipped with roof drilling equipment so as to be able to cope immediately with class III and IV conditions.

5. CONCLUSIONS

This scope of this report has mainly been confined to reviewing the present state of the art of the technology and the costs of machine tunnel boring, and investigating the potential for reducing costs for the construction of the proposed booster tunnel. The main conclusions are:

(a) The time allowed for boring the booster tunnel has been stated to be 2 to 4 years. This includes initial site setup, construction of the access means, and demobilization. There is no particular advantage in completing the work any quicker, as it is understood that the accelerator magnets and associated equipment will not be ready, and therefore the focus becomes almost entirely on cost. Normally, major tunnels are constructed as rapidly as current technology allows, as the tunnel can begin earning revenue or provide a needed service. Rapid excavation also cuts down on total labor costs and reduces interest charges on capital investment.

A high speed tunneling system designed specifically for the particular features of the booster tunnel, and efficiently run, could achieve sustained rates of over 1800 - 2000 meters per month, and therefore the 34 km of tunnel could be completed with one system in about 18 to 20 months, not allowing for some start up delays. Allowing an additional nine months for access construction, system commissioning delays, re-mobilization of the equipment at the half-way point, and demobilization at the end, overall construction time is feasible within 30 months. This assumes that most of the rock is less than 100 MPa UCS.

An alternate consideration is to use two cheaper but slower systems simultaneously, assuming that the total cost of construction for each system is less than half that of the high speed system. The present study has mainly concentrated on feasible technical improvements for the high-speed system, and not examined appropriate specifications and costs of lower powered systems. These could use slower, less capital intensive equipment and smaller work crews. At first glance however, it is difficult to imagine the cost of such a reduced performance system being as much as 50 percent less than a high performance system.

(b) Labor cost has been identified as a major contributor to overall cost, and efforts to reduce it must be made. Labor cost can be reduced in two ways; by getting the job done more quickly and by replacing labor by means of greater automation or by more efficient distribution of the task load.

(c) High excavation speeds can be achieved in the prevailing rock types with conventional TBM technology, and by using cutterhead power levels of the same order that have already been successfully implemented. Existing disk cutter technology appears to be quite adequate, both from the point of view of penetration capability and durability.

(d) Traditionally, the overall advance rates of mechanical tunneling systems have been a low fraction of the TBM's penetration capability. The utilization of the TBM can be improved by improving the efficiency of the boring cycle, and by advancing the technology of the TBM's support system. The long uniform booster tunnels, with constant, but very small curvature provide strong justification for support system improvement and innovation. The introduction of the continuous conveyor principle for tunneling is an example of a mechanized system that has improved overall performance. The time available for limited research and report preparation on the first phase has not permitted in depth conceptual design work. Ideas include substantially increasing the unit length of installed features such as track or segment sections so that fewer units are required, decreasing installation time.

(e) Advanced mechanization of the support systems may result in reduction of manpower. There are practical limits in replacing workers with automated systems or remote controls in the generally hostile underground environment however, particularly as the number of workers needed with TBM systems operation is already quite low.

(f) Reliability of tunneling systems is not as high as would be liked, and a significant, though variable, contributor to system downtime and low utilization factors. Improvement is a somewhat nebulous task however, given the fact that tunneling equipment is mainly custom designed and difficult to test prior to operation, and subject to hostile environmental conditions. A greater level of monitoring of critical systems may help. While improving reliability should be an aim, and uppermost in the mind of the design organization, it will be difficult to gain the kind of quantum advance that is a lot more feasible from innovative mechanical development.

(g) Obtaining useful data concerning the main factors influencing utilization on similar type tunnels has proved to be impossible. While overall utilization rates may be quoted for certain jobs, contractors are generally unwilling to divulge raw data. Even if such records are obtained, meaningful information is usually impossible to extract. The Robbins Company supports the idea of an organized analysis of tunneling operations using data monitoring techniques.

(h) Very long tunnels such as these require tremendous investment in muck haulage and in the transmission of utilities and ventilating air. This may be offset by constructing simple intermediate access shafts to reduce the maximum transport distances. Further study is required to assess the complete cost impact. Alternate forms of power supply such as diesel generation can be studied in greater detail.

(i) The optimum size of tunnel has not yet been determined. With the smallest diameter of 8 feet, the lower corners will need trimming to provide space for vehicles in the operational tunnel. There has been no time in this study for conceptual development of suitable machinery. This development should ideally be made in concert with the tunneling support system development referred to in (c) above, as it is intimately connected with available space in the tunnel for the tunnel construction equipment.

6. RECOMMENDATIONS FOR FURTHER WORK

The phase 1 report has concentrated on providing a technical and cost baseline. The next phase should address specific design issues in detail. Table 19 provides a summary of the recommendations.

(a) For accurate prediction of instantaneous penetration rates along the tunnel alignment, the distribution of rock strength and condition by length along the complete alignment must be documented. Testing of actual samples will be needed to establish baseline rates.

(b) Design study to examine the possibility of approximately doubling the normal TBM gripper stroke of 1.8 meters, and the possibility of installing a double (continuous) gripping system.

(c) Review potential for increasing cutter spacing on cutterhead, which may be possible depending on overall assessment of rock conditions, with aim of reducing power requirements, and producing larger muck chips useful in road construction.

(d) Design studies on support equipment to keep up with a TBM penetration rate of 12 meters per hour. The equipment includes invert segments (if used), guidance track for supply vehicles, electrical, water, and ventilation supply extension.

(e) Design studies on corner trimming tool for small (approximately 8 feet) diameter tunnel to be either attached directly to the TBM, or located independently of the TBM, and means of establishing a smooth flat floor.

(f) Coordinate items (b) and (c) with Fermilab designers to identify most appropriate tunnel size, and the potential for integrating the construction and final configuration requirements e.g. floor design, vehicle track, utilities installation, intermediate shaft access. This will provide the advantages of the "design-build" approach to major civil construction projects.

(g) Begin studies into automation of actual systems to assess overall feasibility, identify technical solutions and costs.

(h) Study means of reducing the cost of delivering muck from the tunnel, and delivery of utilities (mainly electric power) to the TBM system in 17 km tunnels. Methods include the construction of small diameter intermediate access shafts and practical means of local (in or above tunnel) power generation.

(i) Make a dedicated real-time investigation of an actual tunneling operation in similar conditions to those expected on the booster tunnel, to obtain specific reasons for system downtime.

(g) Investigate the feasibility of more economical slower tunneling, in terms of overall cost per meter.

7. REFERENCES

Harza Engineering Company, Geotechnical summary to the proposal to site the superconducting super collider in Illinois; prepared for Dept. of Energy and Natural Resources, Illinois State Geological Survey, 1988 ()

Johannessen, Askilsrud, Meraaker Hydro – tunnelling the "Norwegian Way", RETC Proceedings 1993

Laughton, C, Evaluation and prediction of tunnel boring machine performance in variable rock masses,.Ph.D dissertation, University of Texas, Austin, 1998

Logan, Finnsson, The Blue Mountains sewerage scheme. A case history of the Hazelbrook to Katoomba tunnels, RETC Proceedings 1993

McCormick et al, Analysis of TBM performance at the record setting River Mountains tunnel #2, RETC Proceedings 1997

O'Connor, Economy version of small diameter rock boring, RETC Proceedings 1985

Turner, Carey, Automation of a mobile miner, RETC Proceedings 1993

Tunnel boring machine project data bases and construction simulation, Geotechnical Engineering Report GR94-4, Department of Civil Engineering, University of Texas, Austin, 1994

Reference Material Package provided by Fermilab to Robbins 15 February 1999

Project Date	Geology Strength	Dia (ft) feet	Length m	Max IPR m/h	Best m Month	Average Month	Utilization %	Mucking System	Access Means
Chicago MWRD 1980	*Dolomite*	14	10,800	N/A	1340	771	50	Conveyor	Shaft
Chicago Water 1997	Limestone	18.25	-	-	1513	N/A	N/A	Conveyor	Shaft
River Mountains (CA) 1996	Rhyodacite, Agglomera 20 - 45 Mpa	14.25	6,070	12	1640	1375	36	Conveyor	Portal
Blue Mountains (Aust) 1995	Sandstone 50 - 80 Mpa	11.15	13,400	12	1760	1189	25	Conveyor	Portal
Meraker 1991	Meta-Gabbro, Phyllite 180 - 300 Mpa	11.5	10,000	10.4	1358	1075	40	Muck Train	Portal
SuperCollider (Texas) 1993	Chalk 35 - 55 Mpa	16.4	13,400	N/A	1864	N/A	N/A	Conveyor	Portal

MACHINE SPECIFICATIONS

Project	Mfr	ID	Power	RPM	Cutters
Chicago TARP	Robbins	147-210	670 kW	7.5	31@15.5in
Chicago TARP	Robbins	171-231	*900 kW*	6.5	*39@17in*
River Mountains (CA)	Robbins	129-182	930 kW	12	29@17in
Blue Mountains (Aust)	Jarva	Mk 12	1000 kW	12	25@17in
Meraker	Robbins	1215-265	1340 kW	13.4	25@19in
SuperCollider (Texas)	Robbins	166-245-2	900kW	10	34@17in

TABLE 3. HIGH SPEED PROJECTS - BEST MONTHLY RATES

	8 FOOT DIAMETER		10 FOOT DIAMETER		12 FOOT DIAMETER	
	New Cost	Resale Value	New Cost	Resale Value	New Cost	Resale Value
Basic TBM	2,500,000	800,000	3,250,000	1,000,000	4,000,000	1,500,000
Roof Drills	200,000	50,000	200,000	50,000	200,000	50,000
Elec. Laser Guidance System	150,000	100,000	150,000	100,000	150,000	100,000
Bridge Conveyor	65,000	15,000	70,000	15,000	75,000	15,000
Backup Structure	700,000	125,000	750,000	133,000	800,000	150,000
Dust Scrubber System	30,000	20,000	35,000	23,500	40,000	27,000
Ventilation Duct Cassette	9,000	6,000	10,500	7,500	12,000	8,000
Shotcrete System	50,000	25,000	50,000	25,000	50,000	25,000
Main Transformers	80,000	55,000	90,000	60,000	100,000	66,000
Continuous Conveyor/Meter*+	225	75	225	75	225	75
Electric Cable/Meter*	20	5	23	4	25	5
Ventilation/Meter*	40	25	45	27	53	30
Water Lines/Meter*	15	5	15	5	15	5
Locomotive	120,000	60,000	120,000	60,000	150,000	75,000
Rolling Stock**	250,000	125,000	275,000	137,000	300,000	150,000

* Cost per meter is for long tunnels and includes any booster equipment necessary
** Per set, including material supply cars and personnel car
+ Minimum conveyor size currently available is 24 inch, suitable for range 8' to 12',
Smaller size could be specially developed with lower capital cost, very low residual value

TABLE 4. ESTIMATED CAPITAL COSTS OF MAJOR EQUIPMENT

ROCK TYPE	STRENGTH UCS (Mpa)	RING LIFE CU.M/RING	CUTTER COST/CU.M
Galena Dolomite	69	7002	0.60
Galena Dolomite	52	10724	0.45
Galena Limestone	111	3669	0.93
Platteville Dolomite	84	5226	0.72
Platteville Limestone	157	2216	1.30
AVERAGE	100	4295	0.79

TABLE 5. ESTIMATED CUTTER LIFE AND COST

MAJOR SPARE PARTS COSTS BY TUNNEL DIAMETER

COMPONENT	8 FT DIA	10 FT DIA	12 FT DIA
Main Bearing	$90,000	$165,000	$310,000
Ring Gear	$50,000	$70,000	$75,000
Gear Reducer	$55,000	$55,000	$55,000
Drive Motor	$60,000	$60,000	$60,000

Note: Estimated selling prices, f.o.b. factory

MINOR SPARE PARTS COSTS

Usually estimated at current time as approximately $1.75 per cubic metre of excavation, based on historical usage

Minor spares include such items as:

Cutterhead Bucket Teeth
Conveyor Components
Hydraulic Components such as Hoses, Filters, and Valves
Hydraulic Cylinder Seals
Water System Hardware
Electrical Components such as Lights, Solenoids, Cable

Also consumables such as Hydraulic and Lubrication Oils and Greases

See Table 5 for estimated cutter costs

TABLE 6. ESTIMATED SPARE PARTS COSTS

COMPONENT	DUTY %	POWER (KW)		
		8 FT DIA	10 FT DIA	12 FT DIA
Drive Motors	80	900	1260	1340
TBM Hydraulics	60	75	75	112
Includes:				
Propel System				
Gripper System				
TBM Conveyor				
Bridge Conveyor				
Steering Cylinders				
Lube System	100	5	7.5	15
Material Hoist	25	5	7.5	7.5
Roof, Probe Drills	10	75	75	75
Grout Equipment	5	30	30	30
Shotcrete Equipment	5	30	30	30
Dust Scrubber	100	24	24	24
Water Pumps	30	15	15	15
Drainage Pumps	10	15	15	15
Lighting	100	10	10	10
INSTALLED POWER	-	1185	1550	1675
INSTALLED KVA	-	1600	2050	2200
AVE POWER USAGE	-	900	1150	1250

TABLE 7 TBM SYSTEM INSTALLED POWER AND USAGE

1. ELECTRICAL SUPPLY; TBM & BACK-UP

Refer to Table 7

2. WATER SUPPLIES

	Volume in liters per minute		
	8 foot	10 foot	12 foot
Minimum Supply Requirement	250	250	250
Dust suppression (cutterhead)	40	55	70
Dust suppression (conveyors)	25	25	25
Drive motor/reducer cooling	via dust spray supply and heat exchangers		
Hydraulic power unit cooling			
Lubrication system cooling			
Seal flushing	30	35	40
VF drive cooling (if used)	(150)	(150)	(150)
Scrubber	batch filling		
Rock drill flushing/cooling/drill	120	120	120
Shotcrete application	depends on amount of material applied		
Consolidation grouting			
Washdown	75	75	75

3. COMPRESSED AIR

General tools	
Materials hoist	Air usually supplied by back-up mounted compressor sized to suit application
Shotcrete application	
Rock drill flushing	

4. VENTILATION

	Volume in cubic metre per second		
	8 foot	10 foot	12 foot
(1) Minimum volume at heading	1.40	2.19	3.15
(2) Volume per worker	0.094	0.094	0.094
(3) Volume/diesel bhp	0.047	0.047	0.047

Note: (1) must be at least the sum of (2) and (3), but cannot be less than the value stated.
MSHA Regulations 30 CFR 75.

TABLE 8. UTILITY SERVICES CONSUMPTION IN TUNNEL

TUNNELING COST REDUCTION STUDY

12 FOOT OPEN GRIPPER TBM IN HARD GROUND

TUNNEL HEADING CREW

USA – MUCK REMOVAL BY CONTINUOUS CONVEYOR

Note: If ground support is required, two additional workers for rockbolting, arches, or shotcreting.

Per Shift

1	Shift Boss
1	TBM operator
2	Continuous conveyor operators
2	Track and utilities installers
1	Mechanic
1	Electrician
1	Locomotive driver

Total 11

NORWAY – MUCK REMOVAL BY TRAIN

Per Shift

1	TBM operator
1	Mechanic
1	Electrician
1	Locomotive driver

Total 4

SHAFT BOTTOM AND SURFACE CREW

Per Shift

1	Crane Operator
2	Conveyor/Muck Dumping Supervisors
2	Laborers

Total 5

TABLE 9. COMPARISON OF TBM CUTTERHEAD DRIVE OPTIONS

Current Local Practice in USA

Project Management, Engineering, and Operations

Project Manager
Tunnel Superintendent
Equipment Superintendent
Maintenance Manager
Tunnel Walkers
Project Engineer
Office Engineer
Tunnel Engineer
Estimator/Scheduler
Purchasing/Expeditor
Safety Manager
Safety Engineer

Clerical

Office Manager
Clerk/Secretary
Timekeeper

TABLE 10. INDIRECT LABOR REQUIREMENTS

FEATURE	SINGLE SPEED	2-SPEED	VARIABLE FREQUENCY	HYDRAULIC
Speed Variation	None	Two speeds	Zero to full speed	Zero to full speed
Constant Power Range	None	2:1 normal max	1.7:1	4:1
Temporary Overload	100% +	100% +	100% +	20% +
Inertia (Flywheel Effect)	High	High	High	Low
Efficiency (Mech)	95 %	95%	92%	66%
Power Factor	0.85	0.85	1.0	0.85
Reliability	Very High	Very High	High	Moderate
Blocked Head Start	Inertia Breakout	Inertia Breakout	Sustained High Torque	Sustained High Torque
Heat Output	Low	Low	Low	High
Noise Level	Moderate	Moderate	Moderate	High
Additional Cost @1200 kW	0	$50,000	$200,000	$200,000

TABLE 11. COMPARISON OF TBM CUTTERHEAD DRIVE OPTIONS

12 FOOT DIAMETER OPEN GRIPPER TBM IN 100 MPA LIMESTONE

♦ Theoretical Instantaneous Penetration Rate	10.9 m/hour
♦ Cutter Size	17 inch
♦ Penetration per Revolution	13 mm
♦ Maximum Allowable Force per Cutter	267 kN
♦ Force per Cutter @ 13 mm Penetration	174 kN
♦ Cutterhead RPM	14
♦ Gripper Stroke	10 feet
♦ Regrip Time	3.5 mins
♦ Cutter Ring Life	4295 cu.m
♦ Cutter Quantity	26
♦ Installed Cutterhead Power	1340 kW
♦ Estimated Power Consumption per Metre	125 kWhr

TABLE 12. PROPOSED TBM SPECIFICATION

TUNNELING COST REDUCTION STUDY

BOOSTER TUNNEL ALIGNMENT IN COMPETENT GROUND

MACHINE DIAM:	12.0 ft.	TORQUE:	777 kNm
THRUST:	6,948 kN	CUTTER DIAMETER	17 in
C'HD POWER	1340 kW	NO. CUTTERS:	26
RPM:	14	MAX CUTTER LOAD	267 kN
DRIVE EFF'Y	85 %	CUTTER TIP WIDTH	12 mm

ROCK	UCS MPa	NTH CLASS*	CUTTER LOAD kN	CUTTER PEN. mm	INSTANTANEOUS PEN. RATE m/hr	C'HEAD SP. ENERGY kWhr/cu.m
Galena Dolomite	69	1	148	18	13.7 - 15.8	7
Galena Dolomite	52	1	129	23	18.3 - 21.0	6
Galena Limestone	111	1	183	12	9.1 - 10.5	11
Platteville Dolomite	84	1	163	15	11.3 - 13.0	9
Platteville Limestone	157	1	216	8	6.6 - 7.5	15
AVERAGE	**100**	**1**	**174**	**13**	**10.2 - 11.7**	**10**

* NTH (Univesity of Trondheim) Fracture Classification Average 40 cm Spacing

TABLE 13. PRELIMINARY TBM PERFORMANCE ESTIMATES

ELEMENTS OF THE REGRIP CYCLE:

1. Switch off propel system
2. Disconnect automatic thrust control system (cruise control) if in use
3. Allow cutterhead to rotate a few revolutions to clear out muck
4. Disconnect cutterhead drive clutches (fixed speed drives)
5. Reduce cutterhead speed to zero (variable speed drives)
6. Stop conveyors
7. Note machine alignment from laser targets
8. Lower rear legs until weight of machine is taken by the legs (machine rear end moves upward and/or pressure indicated at leg cylinders)
9. Switch gripper hydraulic system from high pressure to reset mode
10. Retract gripper shoes sufficiently to clear any wall obstruction
11. Retract propel cylinders
12. Extend grippers, ensuring that both sides contact the wall simultaneously
13. Switch to gripper high pressure mode to ensure secure gripping
14. Pressurize the vertical steering cylinders to prevent slight dropping of rear end
15. Retract rear legs to clear any obstacles
16. Sound siren for a few seconds to announce conveyor start up
17. Restart bridge and machine conveyors in order
18. Sound siren for a few seconds to announce boring restart
19. Engage clutches, or ramp up cutterhead speed on variable drive
20. Adjust machine alignment to original or corrected position per laser target
21. Starting at 50 percent propel flow, gradually ramp up propel pressure
22. When desired propel rate/motor load reached switch to automatic thrust

Estimated average overall cycle time - 4 minutes: variables include required amount of gripper and rear leg retraction, steering corrections, operator skill, and disruptive effect of the stop itself.

Regrip Time Improvement Options

	Standard Stroke 6 feet	**Long stroke 10 feet**
Basic Regrip Cycle Time	4.0	5.0
High Volume Propel Pump	3.25	3.75
Automated Sequencing and Steering corrections	2.75	3.25
Leave Continuous Conveyors Running	2.5	3.0

TABLE 14. DECREASING REGRIP TIME ON OPEN GRIPPER TBM

Problem	Probability/ MTBF[1]	Design Standards	On-site Repair	Repair Tasks	Contingency Planning	Downtime
Main bearing failure	Rare >10,000 hr	Lifetime calculations Two-piece bearing	Bearing Replacement	Cutterhead removal Manual excavation for one-piece bearing	Bearing on consignment Condition monitoring	2 – 6 weeks
					None	up to 9 months
Seal failure	Infrequent >2,000 hr	Seal design, lubrication, flushing, and protection	Seal replacement	Cutterhead removal (inner seals)	Spare seals	1 – 2 weeks
Ring gear failure	Very rare >10,000 hr	Lifetime calculation Separate bearing and gear Two-piece gear Reversibly mounted	Gear replacement	Cutterhead removal	Gear on consignment	2 – 4 weeks
					None	up to 6 months
Drive motor failure	Infrequent >3,000 hr	Approved manufacturer Spare drive installed	Replace motor	Depends on access	Spare motor Run with reduced power	One day
Gear reducer failure	Infrequent >3,000 hr	Approved manufacturer	Replace reducer	Depends on access	Spare reducer Run with reduced power	One day
Clutch failure (if used)	Infrequent >3,000 hr	Approved manufacturer Quick change capability	Replace clutch or plates	Depends on design	Spare clutch and plates Run with reduced power	Two shifts
Structural failure, including welds and bolts	Design-infrequent Accident-moderate	Material standards Welding standards Design safety factors Good design	Field welding	Depends on accessibility	Frequent inspection	1 shift (minor) 1 month (major)
Conveyor belt failure	Fairly Infrequent >1,000 hr	Conveyor standards Approved manufacturer Detail design	Replacement or splicing	Depends on accessibility Belt must be dragged	Frequent inspection	1 shift
Electrical failures PLC problems	Moderate >250 hr	Approved manufacturer Proper sizing	Replacement Replacement	Depends on accessibility	Spares on site Electrical and electronic service support	1 shift (minor) 2 days (major)
Hydraulic/ lube system failures: Components Leakage Overheating	Moderate >250 hr	Approved manufacturer Adequate filtration Assembly quality Correct sizing	Replacement Redundancy in critical circuits	Depends on accessibility	Fluid condition monitoring Spares on site Hydraulic service support Condition monitoring	1 shift (minor) 2 days (major)

Note 1. The MTBF figures are for general guidance only, representing a perceived failure rate across all TBM systems. Because TBM equipment is mainly custom designed, and subject to a wide range of operating conditions, it is considered impossible to predict the specific likelihood of breakdown on any single project. For further discussion refer to the text in paragraph 3.4.2.5.

TABLE 15. TBM SYSTEM BREAKDOWN AND REPAIR ASSESSMENT

TUNNELING COST REDUCTION STUDY

12 foot diameter open gripper TBM in 100 MPa competent rock in 17,000 meter tunnel

	SYSTEM FEATURES	METERS PER DAY	UTIL'N	WORKING DAYS	DAYS SAVED	
					BASE IPR	HIGH IPR
1	Base IPR (6m/h)	66.6	46	255	-	-
2	High Rate (10 m/h)	88.0	37	193	62	-
3	Faster Regrip	91.1	38	187	69	6
4	Automatic Regrip	93.2	39	182	73	11
5	Double Stroke	98.2	41	173	82	20
6	Conv. Run @ Regrip	98.9	41	172	83	21
7	Continuous Gripping	107.2	45	159	97	35
8	Continuous Conveyor	117.6	49	145	111	49
9	Mech Track Installation	130.2	54	131	125	63
10	Reduced Maintenance	144.4	60	118	138	75
11	Reliability Improvement	149.8	62	113	142	80

Start-up period and "learning curve" not allowed for. Allow 50 additional days overall

NOTES ON FEATURES

1. Average normally planned rate today
2. Achievable rate in competent rock by state of the art machine
3. Decrease regrip time from 4 minutes to 3.25 minutes
4. Automate regripping functions saving 30 seconds per cycle
5. Increase stroke to 3.5 meters, overall regrip time 3.5 minutes
6. Keep cutterhead and conveyor system running during regrip
7. Add extra set of grippers for continuous gripping
8. Reduce transport delays by at least 50 percent
9. Reduce track laying delays by at least 50 percent
10. Reduce maintenance by at least 50 percent
11. Reduce unrelibaility factor by at least 50 percent

TABLE 16. CUMULATIVE PERFORMANCE IMPROVEMENT

12 foot diameter open gripper TBM in 100 MPa competent rock in 17,000 meter tunnel

Standard Speed TBM - 6 meter/hour IPR

	SYSTEM FEATURES	METERS PER DAY	UTIL'N	WORKING DAYS	DAYS SAVED
1	Base IPR (6m/h)	66.6	46	255	-
3	Faster Regrip	68.3	47	249	6
4	Automatic Regrip	69.5	48	245	11
5	Double Stroke	71.9	50	236	19
6	Conv. Run @ Regrip	67.1	47	253	2
7	Continuous Gripping	77.0	53	221	35
8	Continuous Conveyor	70.4	49	241	14
9	Mech Track Installation	70.4	49	241	14
10	Reduced Maintenance	73.9	51	230	25
11	Reliability Improvement	67.8	47	251	5

High Speed TBM - 10 meter/hour IPR

	SYSTEM FEATURES	METERS PER DAY	UTIL'N	WORKING DAYS	DAYS SAVED
2	Base IPR (10m/h)	88.0	37	193	-
3	Faster Regrip	91.1	38	187	6
4	Automatic Regrip	94.3	39	180	13
5	Double Stroke	97.6	41	174	19
6	Conv. Run @ Regrip	89.0	37	191	2
7	Continuous Gripping	107.2	45	159	35
8	Continuous Conveyor	94.9	40	179	14
9	*Mech Track Installation*	94.9	40	179	14
10	Reduced Maintenance	97.7	41	174	19
11	Reliability Improvement	90.2	38	188	5

Start-up period and "learning curve" not allowed for. Allow 50 additional days overall

See notes on Table 16

TABLE 17. INDIVIDUAL PERFORMANCE IMPROVEMENT

TUNNELING COST REDUCTION STUDY

12 foot diameter open gripper TBM in 100 MPa competent rock in 17,000 meter tunnel

Standard Speed TBM - 6 meter/hour IPR

	SYSTEM FEATURES	METERS PER DAY	UTIL'N	WORKING DAYS	DAYS SAVED	
					BASE IPR	HIGH IPR
1	Base IPR (6m/h)	66.6	46	255	-	-
2	Base IPR (10m/h)	88.0	37	193	62	-
3	Faster Regrip	91.1	38	187	69	6
4	Automatic Regrip	93.2	39	182	73	11
5	Double Stroke	98.2	41	173	82	20
6	Conv. Run @ Regrip	98.9	41	172	83	21
7	Continuous Gripping	107.2	45	159	96	35
8	Continuous Conveyor	117.6	49	145	110	49
9	Mech Track Installation	130.2	54	131	124	63
10	Reduced Maintenance	144.4	60	118	137	75
11	Reliability Improvement	149.8	62	113	142	80

Start-up period and "learning curve" not allowed for. Allow 50 additional days overall

NOTES ON FEATURES

1. Average normally planned rate today
2. Achievable rate in competent rock by state of the art machine
3. Decrease regrip time from 4 minutes to 3.25 minutes
4. Automate regripping functions saving 30 seconds per cycle
5. Increase stroke to 3.5 meters, overall regrip time 3.5 minutes
6. Keep cutterhead and conveyor system running during regrip
7. Add extra set of grippers for continuous gripping
8. Reduce transport delays by at least 50 percent
9. Reduce track laying delays by at least 50 percent
10. Reduce maintenance by at least 50 percent
11. Reduce unreliability factor by at least 50 percent

TABLE 17. CUMULATIVE PERFORMANCE IMPROVEMENT

Current Standard Monitoring	Past and Current R & D	Future	
		Condition Monitoring	R & D
Penetration Rate	Individual Cutter Forces	Cutter Wear	Performance Investigation: System Activity Monitoring on Specific Projects [1]
Cutterhead RPM	Bearing Loading	Cutter Blockage	
Cutterhead Torque	Cutterhead Support Vibration	Blocked Muck Bucket	
Cutterhead Thrust		Main Bearing Vibration	
Gripper Force		General Component Vibration	
Mucking System Video		Bearing Loading	
		Sub-system Power/Pressure	
		Hydraulic Oil Contamination	
		Lube Oil Contamination	
		Ground Condition [2]	

Notes:

1. Identify operations and causes of delay on ongoing real time basis.
2. Seismic/Radar systems still in developmental stage.

TABLE 18. TBM SYSTEM MONITORING OPTIONS

AREA	WORK	BENEFIT
Geology	1. Refine knowledge of distribution of rock strength and quality. 2. Obtain samples for boreability and wear assessment.	Determine baseline for excavation rates and cutter costs
TBM Advance Rate	Review longer gripper stroke and continuous gripping	Decrease regrip time
TBM Cutterhead Design	Determine potential for cutter spacing increase	1. Power reduction 2. Larger muck chips may have higher market value
TBM Support	Match tunnel facilities extension rate to TBM excavation rate: Includes segment installation and utilities advance	Improve utilization
Tunnel Section	Investigate feasibility of integrated tunnel trimming device and construction of smooth flat floor	Reduce tunnel size, eliminate segments
Tunnel design	Integrate tunnel construction methods with final design requirements. Includes shaft access optimization for mucking, utility supply	Obtain benefits of "design-build" approach now becoming popular for large scale projects
Automation	Review functional requirements of candidate systems and specify methods and components	Potential manpower reduction
Power Supply	Review alternate power sources and means of transmission	Reduction of power delivery cost
Utilization Improvement	In-depth study of similar actual TBM operation supported by instrumentation and monitoring	Improved operating efficiency
Number of TBMs	Assess critical path. Compare relative costs of high performance system and limited performance systems.	Determine most cost effective solution

TABLE 19. RECOMMENDATIONS FOR FURTHER WORK

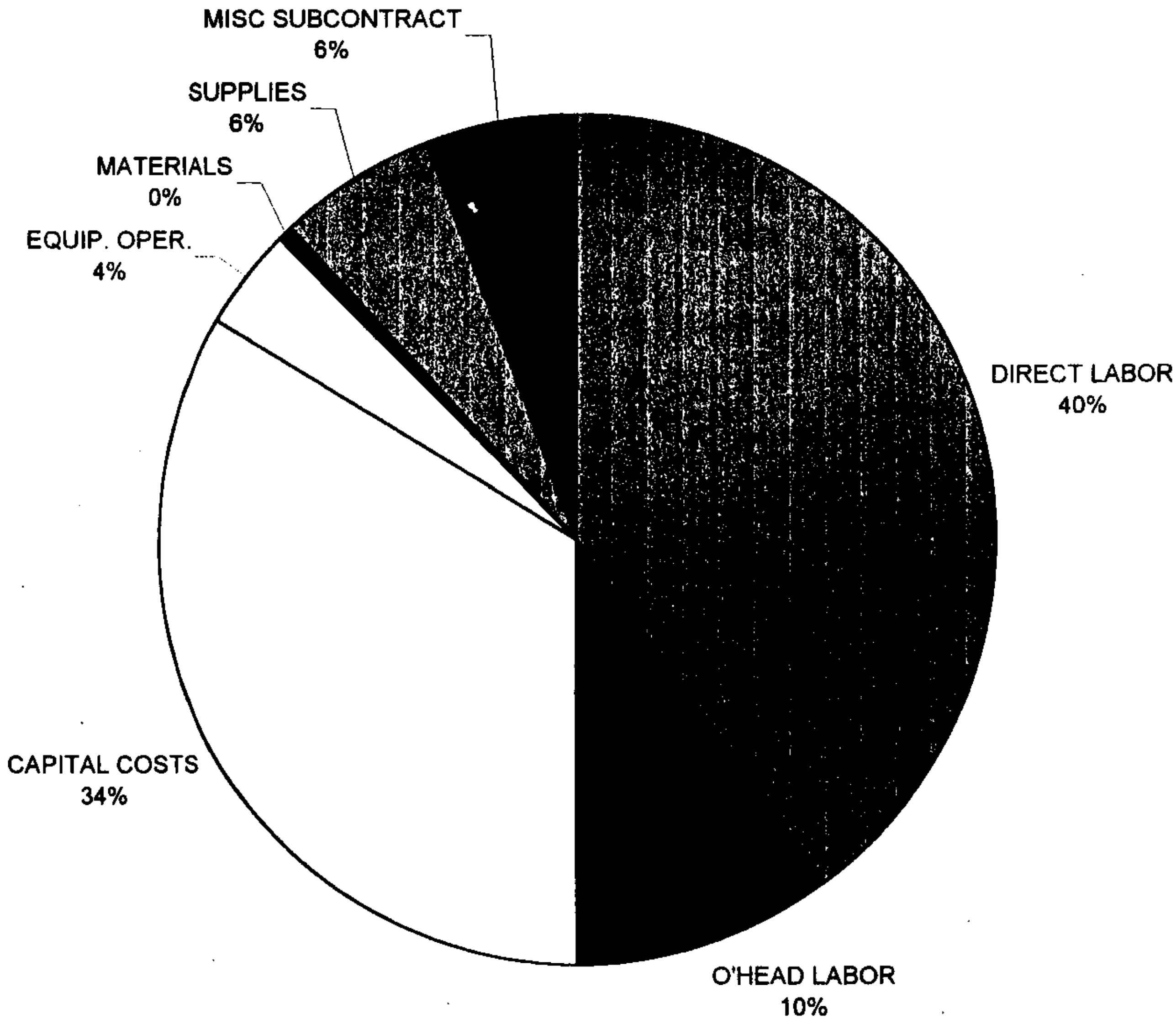


FIGURE 1. PROJECTED COST DISTRIBUTION OF CURRENT TUNNELING PLAN

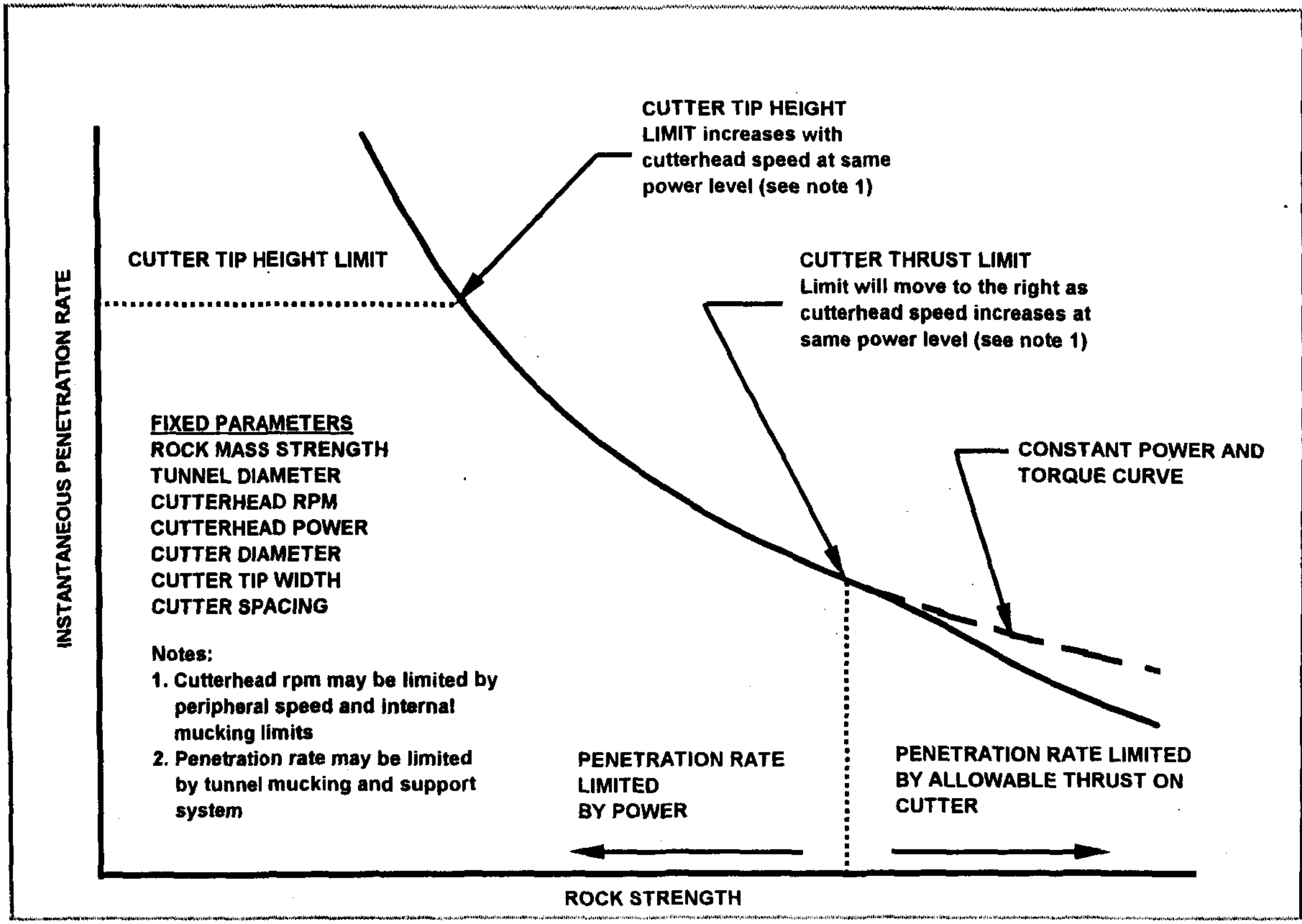
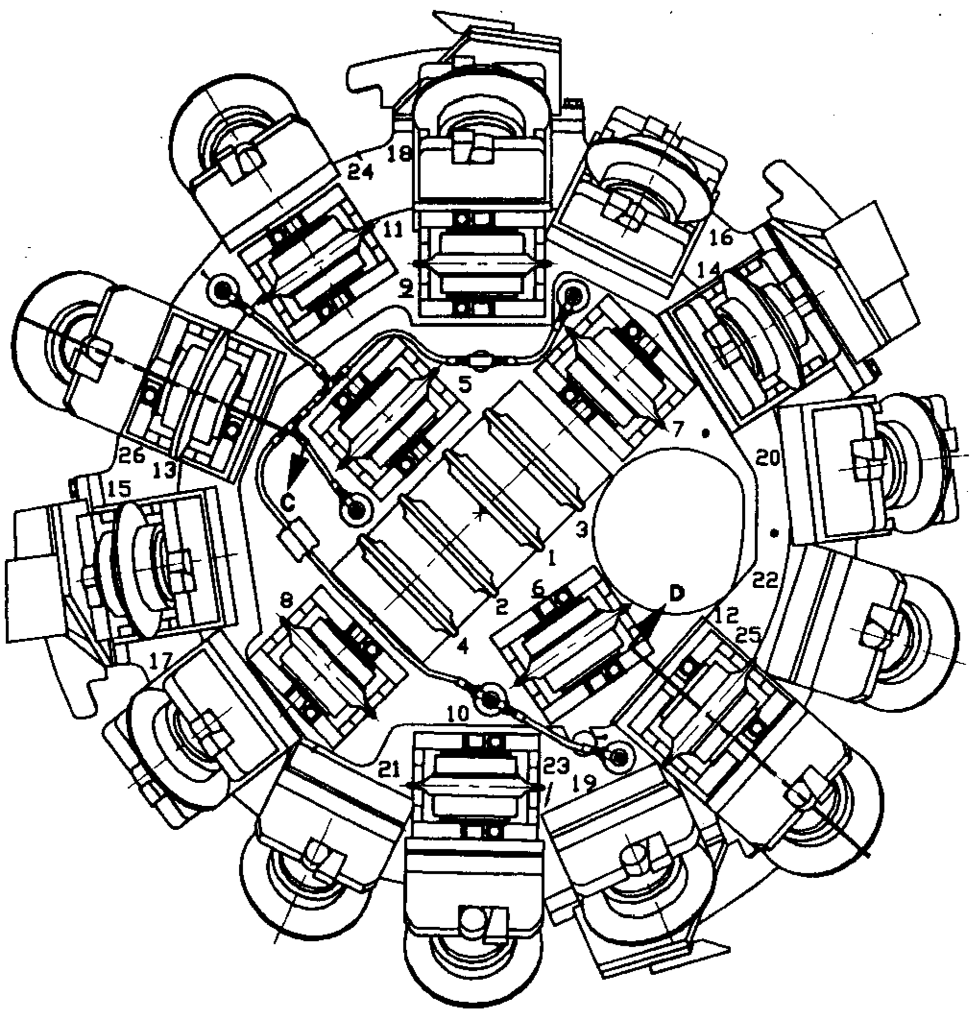
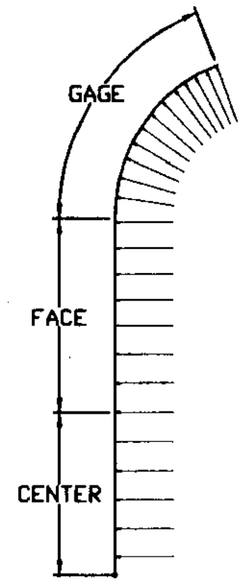


FIGURE 2 - INSTANTANEOUS PENETRATION RATE VERSUS ROCK STRENGTH

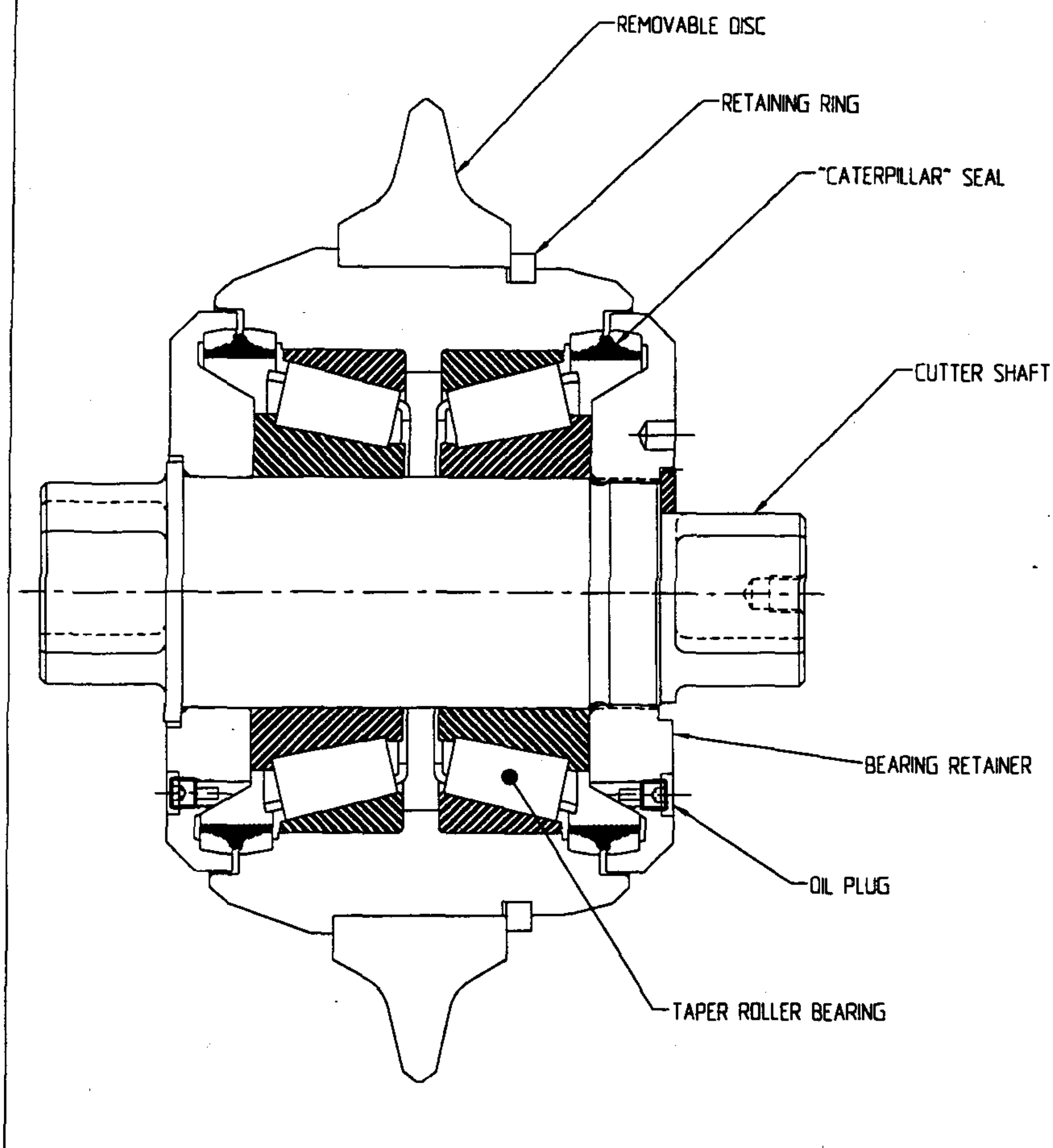




CUTTER PROFILE

TYPICAL 10 FT DIA RANGE FRONT LOADING CUTTERHEAD

FIGURE 3



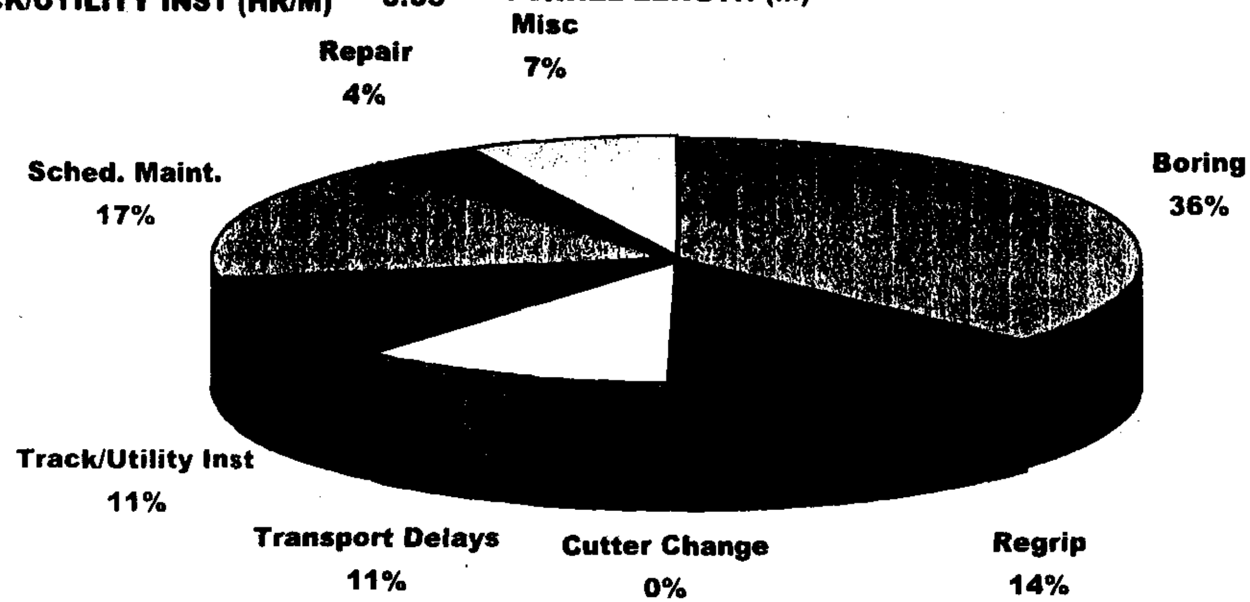
TYPICAL DISC CUTTER ASSEMBLY

FIGURE 4

FERMILAB TUNNELING COST REDUCTION STUDY

DATA INPUT

IPR (M/HR)	10.0	SCHED. MAINT. (HR/DAY)	4.00
BORING STROKE (M)	1.8	REPAIRS (HR/M)	0.01
REGRIP TIME (MIN)	4.0	MISC DELAYS (HR/HR)	0.08
TRANSPORT DELAYS (HR/M)	0.03	CUTTER LIFE (HOURS)	1049
TRACK/UTILITY INST (HR/M)	0.03	TUNNEL LENGTH (M)	17000



Note: Cutter changes done during maintenance

DATA OUTPUT

NET ADVANCE/HR	3.67
TOTAL WORKING DAYS	193

FIGURE 5. TYPICAL TBM UTILIZATION PIE CHART

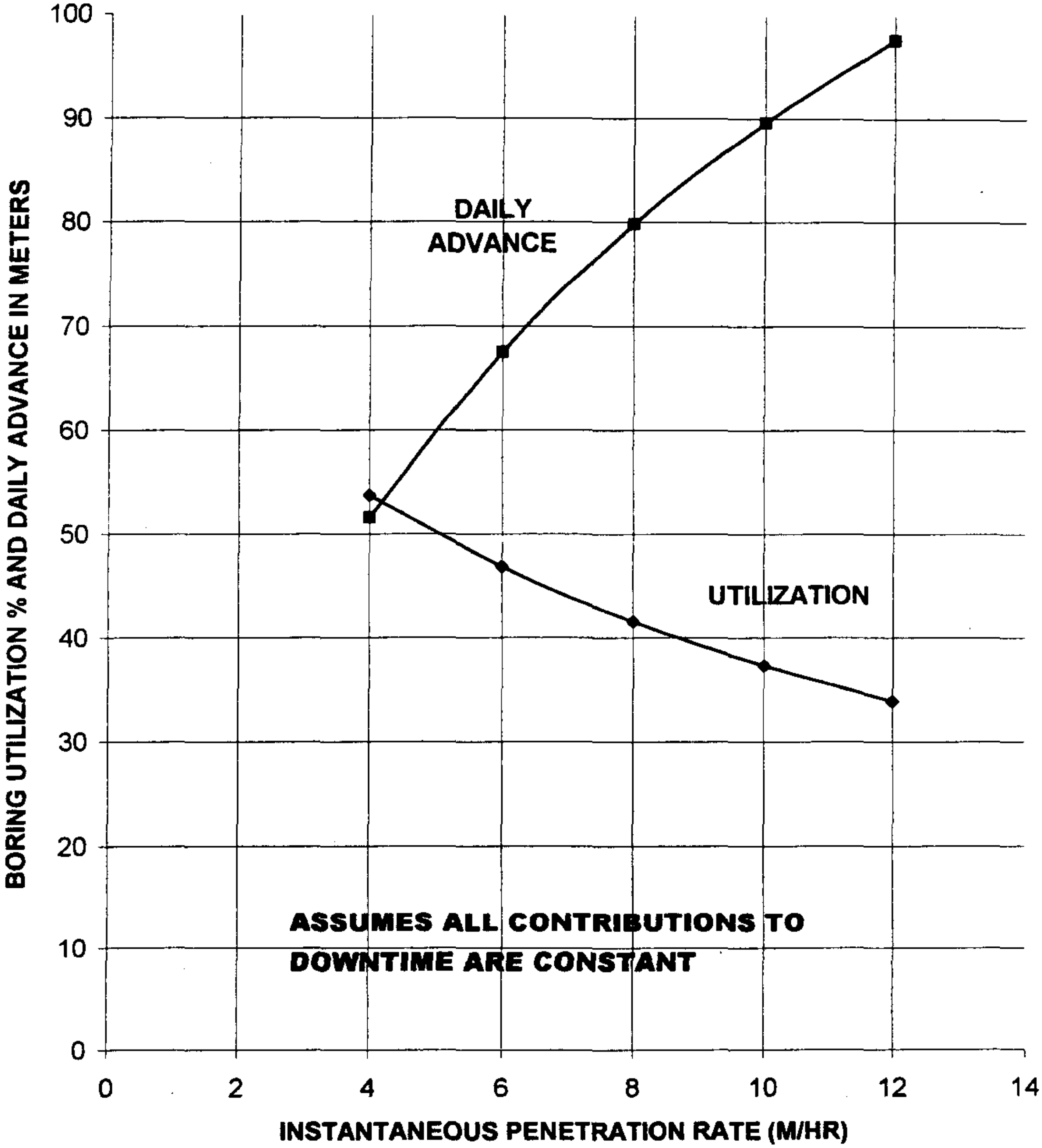


FIGURE 6. GENERALIZED RELATIONSHIP BETWEEN IPR AND UTILIZATION

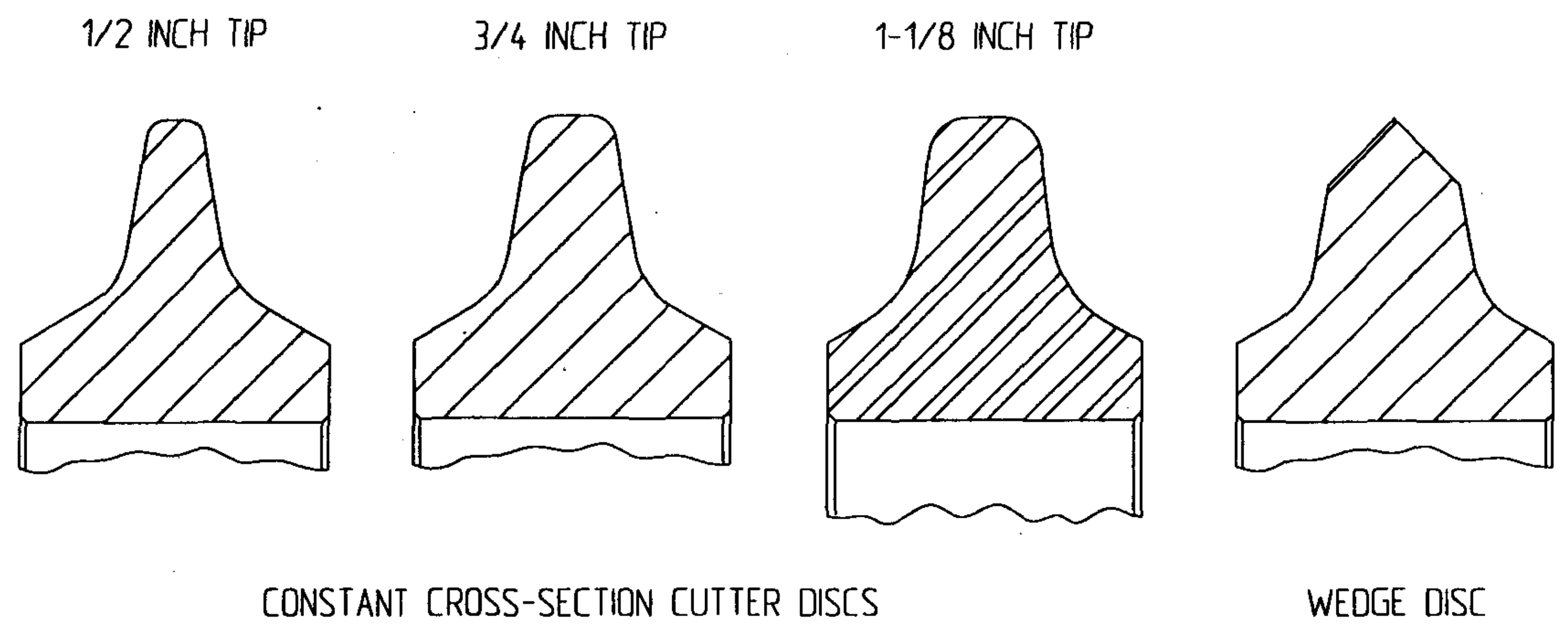
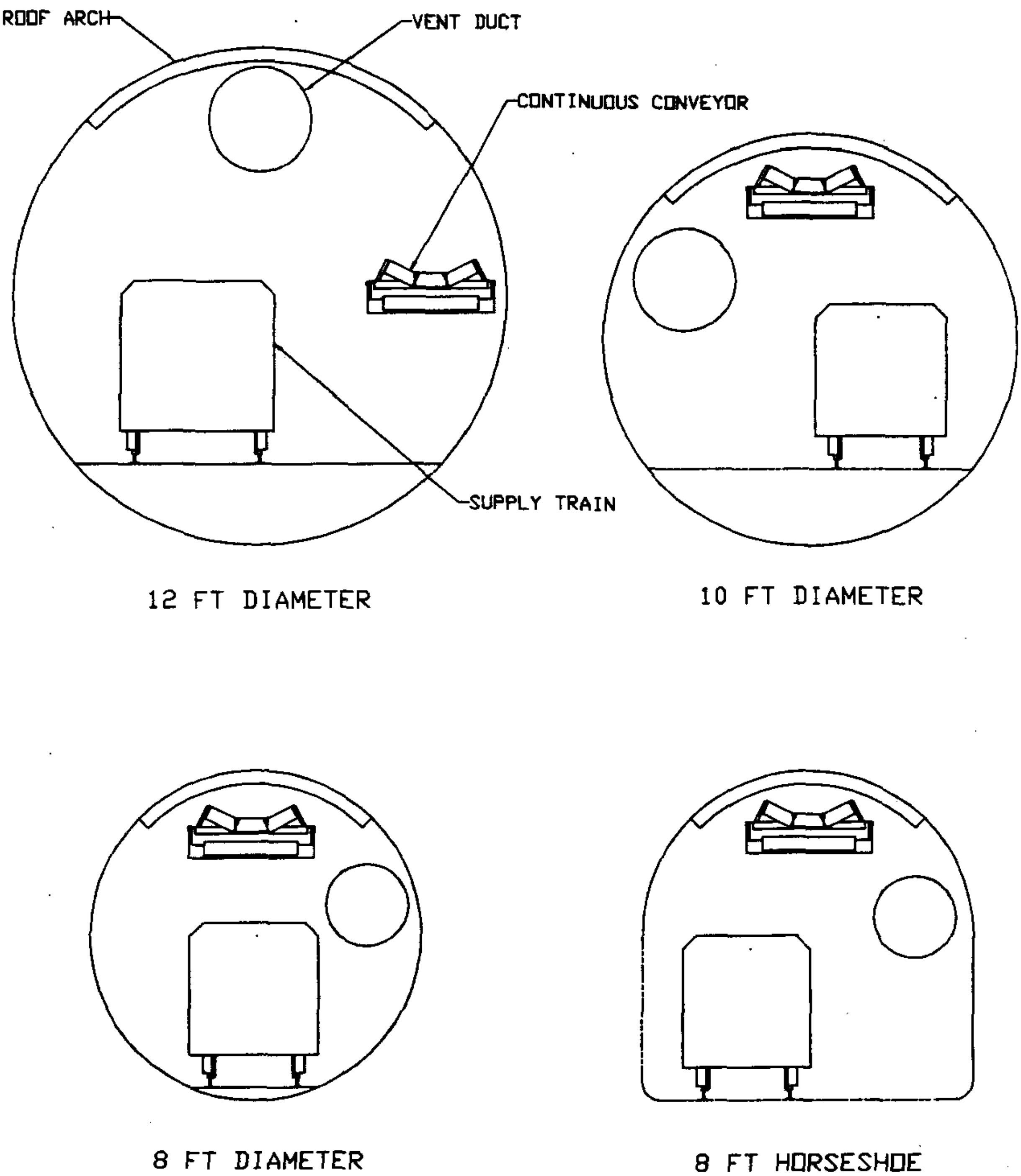
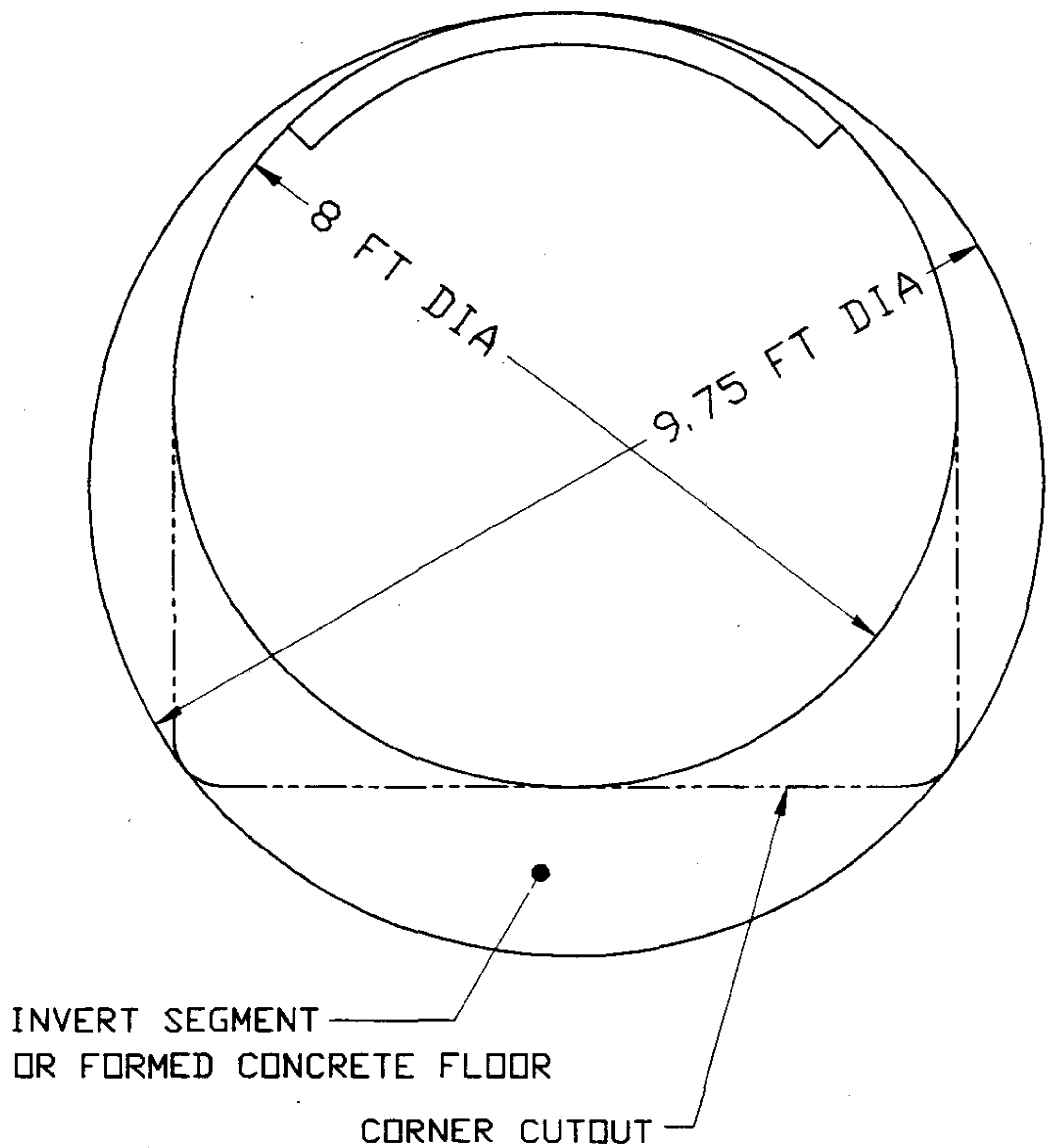


FIGURE 7 TYPICAL CUTTER DISC CROSS SECTIONS



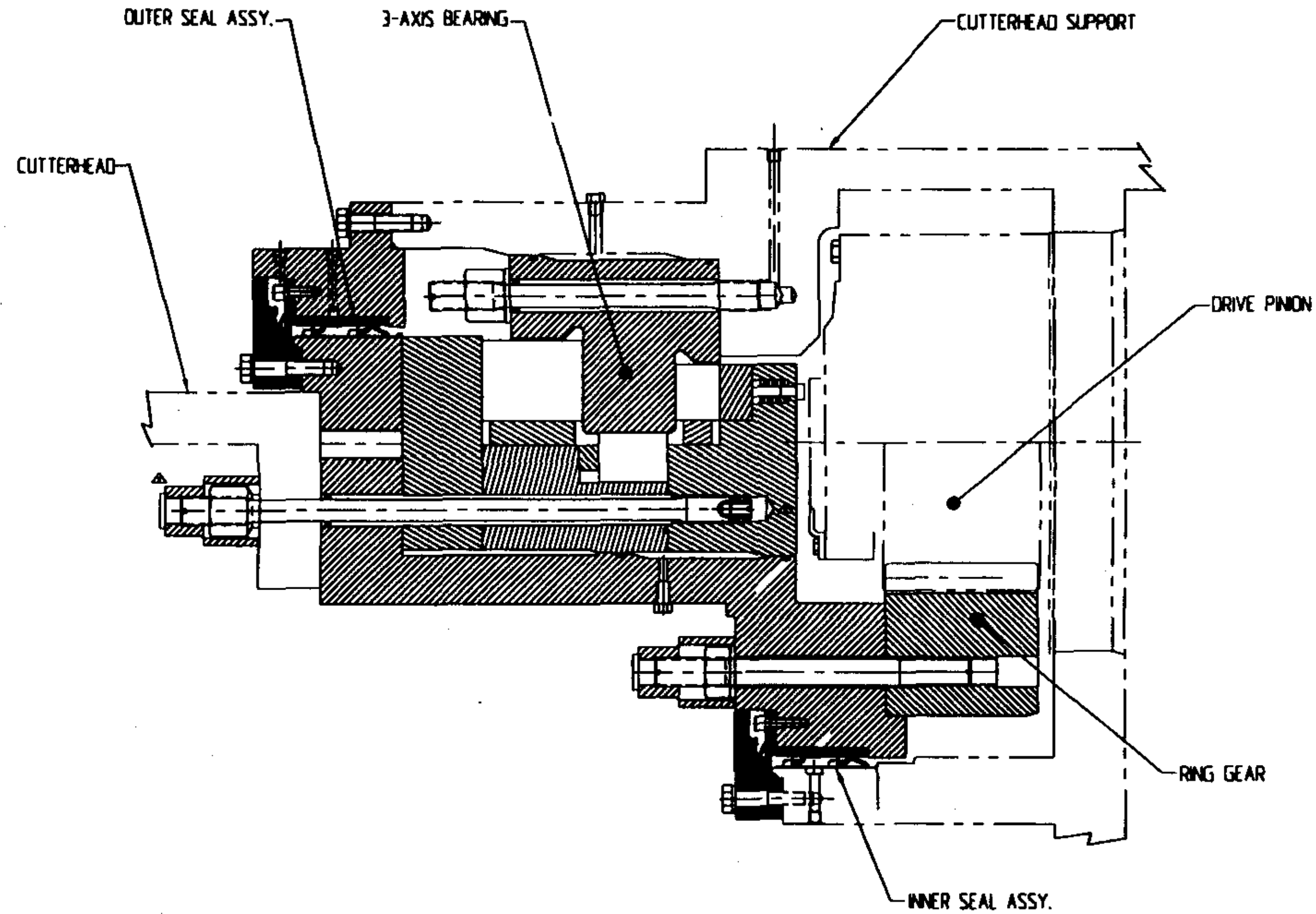
TUNNEL CROSS-SECTIONS FOR VARIOUS DIAMETERS

FIGURE 9



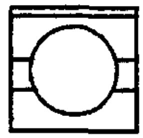
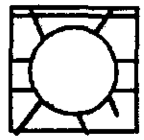
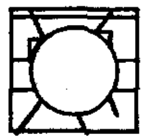
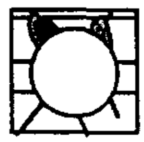
COMPARISON OF HORSESHOE AND CIRCULAR SECTIONS
AT MAXIMUM RANGE

FIGURE 10

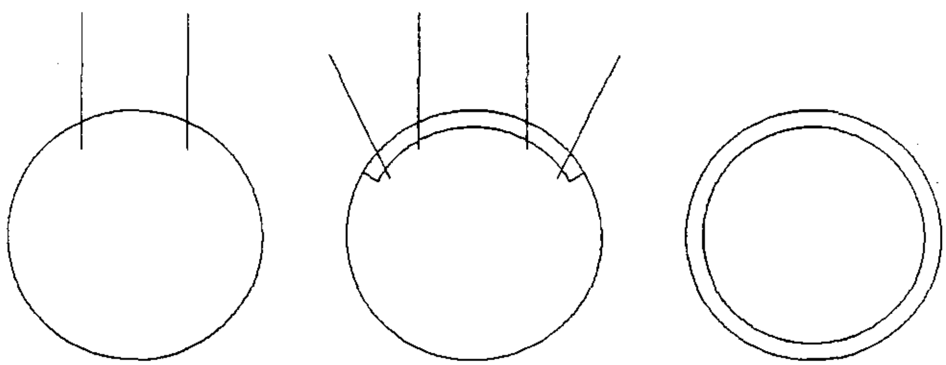


TYPICAL MAIN BEARING AND SEAL ASSEMBLY AND FINAL DRIVE

FIGURE 11

Behavior-Classes	Evidence of Instability at the Heading	
I: Field-Massive	• bedding only • no mapped joints	
II: Fractured But Stable	• mapped joints present • no overbreak	
III: Local Fracture-Bound Overbreak	• local overbreak • limits of overbreak defined by planar fracture surfaces	
IV: Local Soil-Like Overbreak "Pockets"	• local overbreak • limits of overbreak defined by uneven weathered/altered surfaces	
V: Extreme Mining Areas	• extended overbreak length • heavily fractured and/or altered/weathered materials	

ROCK CONDITION CLASSES



Class I-II - 93%	Class III – 6%	Class IV – 1%
2 x 1.8 m bolts	4 x 1.8 m bolts & 50% canopy	ribs & 50% canopy

APPROPRIATE SUPPORT METHODS

FIGURE 12

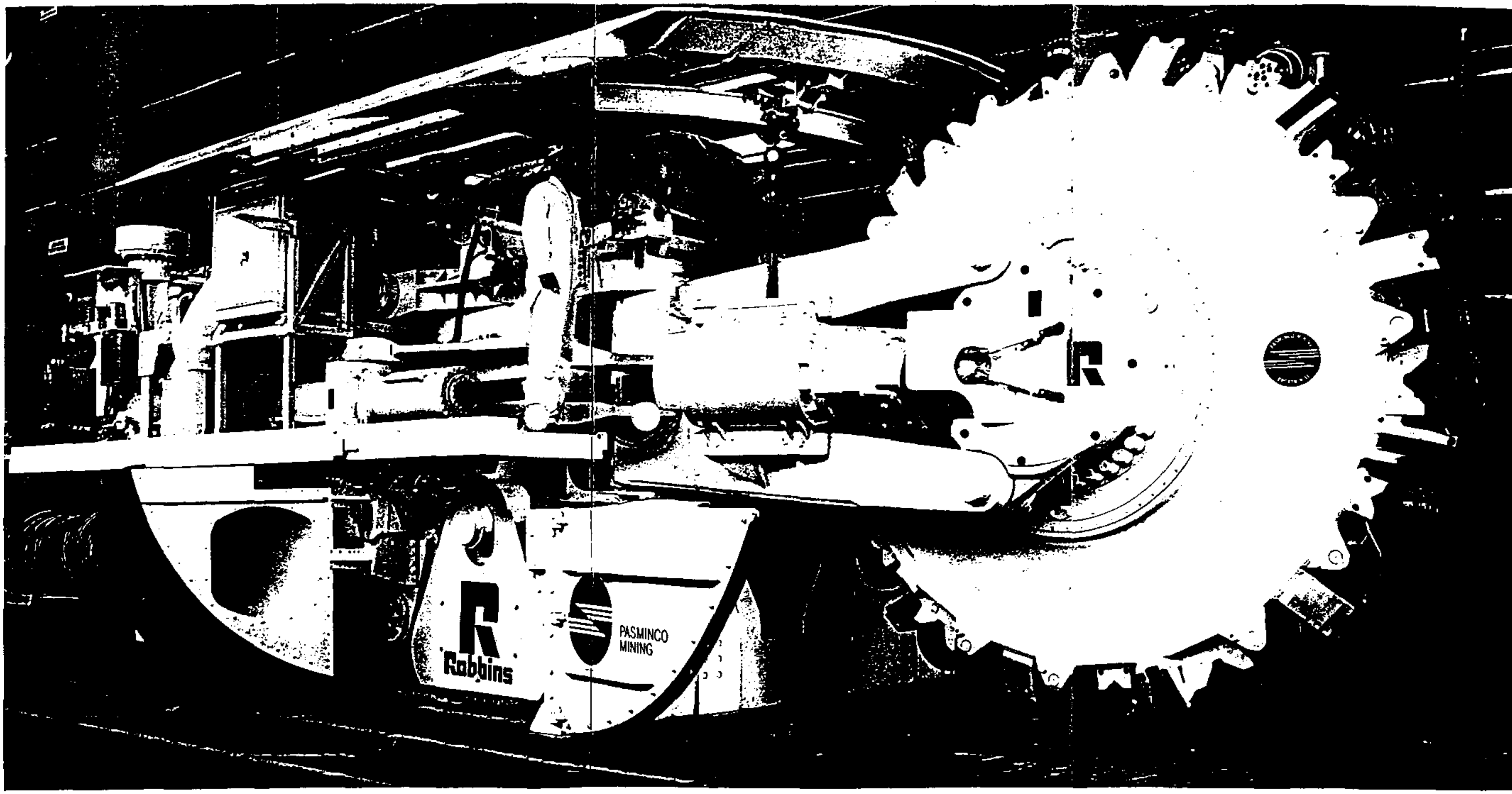
PHOTOGRAPHS AND BROCHURES

OF TUNNEL BORING MACHINERY

achine Made for Hard Rock Mining

e Mobile Miner was developed to ne mechanically what until now could y be done by drill and blast. And to bring more speed, safety and efficiency to underground mining operations. Forty years of mechanical ard rock excavation experience and over ten years of mine-tested concept development have been built into the Robbins Mobile Miner.

The Robbins Mobile Miner Uses Proven Rock Boring Technology and a Patented Cutting System

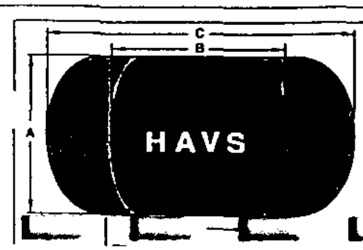


erground Mining

VS:

Mobile Miner HAVS (Horizontal erwheel Axis and Vertical Swing axis) ates a flat floor and roof and elliptical side ls. HAVS is the simplest Mobile Miner fig nd is for b

MODEL	DIMENSION A Excavation Height	B Minimum Width	C Maximum Width	D Minimum Floor	E Maximum Floor
110	3.5m	3.5m	6.6m	2.0m	4.3m
120	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
130	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



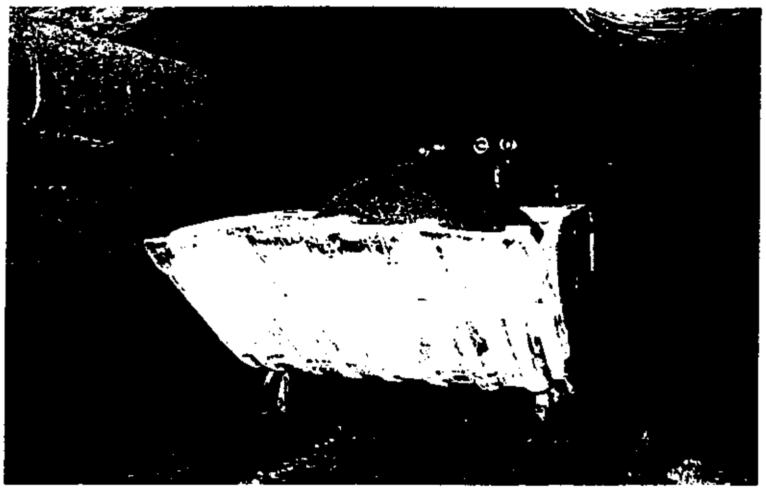
HATS:

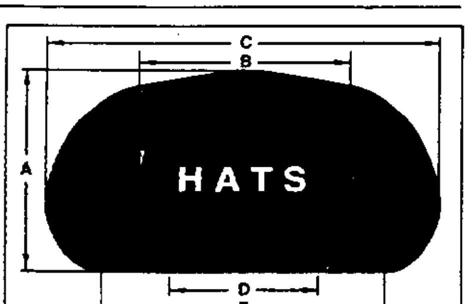
The Mobile Miner HATS (Horizontal cutterwheel Axis and Tilt Swing axis) incorporates a pitching boom which produces an arched roof and the widest flat floor possible. This configuration is ideal for development work or ore production where grou tions arch

MODEL	DIMENSION A Excavation Height	B Minimum Width	C Maximum Width	D Minimum Floor	E Maximum Floor
110	3.5m	3.5m	6.4m	2.5m	5.0m
120	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
130	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
140	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Like Robbins' tunnelling machines and raise drills, which are recognized worldwide for rapid underground excavation, the Mobile Miner employs disc cutter technology for the most efficient excavation of hard rock. The Robbins Company pioneered this rock boring technology and has more experience designing machines for boring rock than any other company in the world.

This technology, when combined with the Mobile Miner's patented cutting system, produces a clean tunnel with a flat floor and roof and variable width.





Comparison of Excavation Methods
The Mobile Miner provides benefits unmatched by any other hard rock underground mining machine or method

FEATURE	M M	TBM	D & B
Flat or arched roof	X		X
Cut hard rock	X	X	X
Short radius curve	X		X
Mobile self-propelled	X		X
Continous operation	X	X	
Clean air environment	X	X	
Shock free excavation	X	X	
Low noise levels	X	X	
Automated operation	X	X	
Precision excavation	X	X	
Graded muck	X	X	
Variable cross section	X		X
Reduced ground support	X	X	

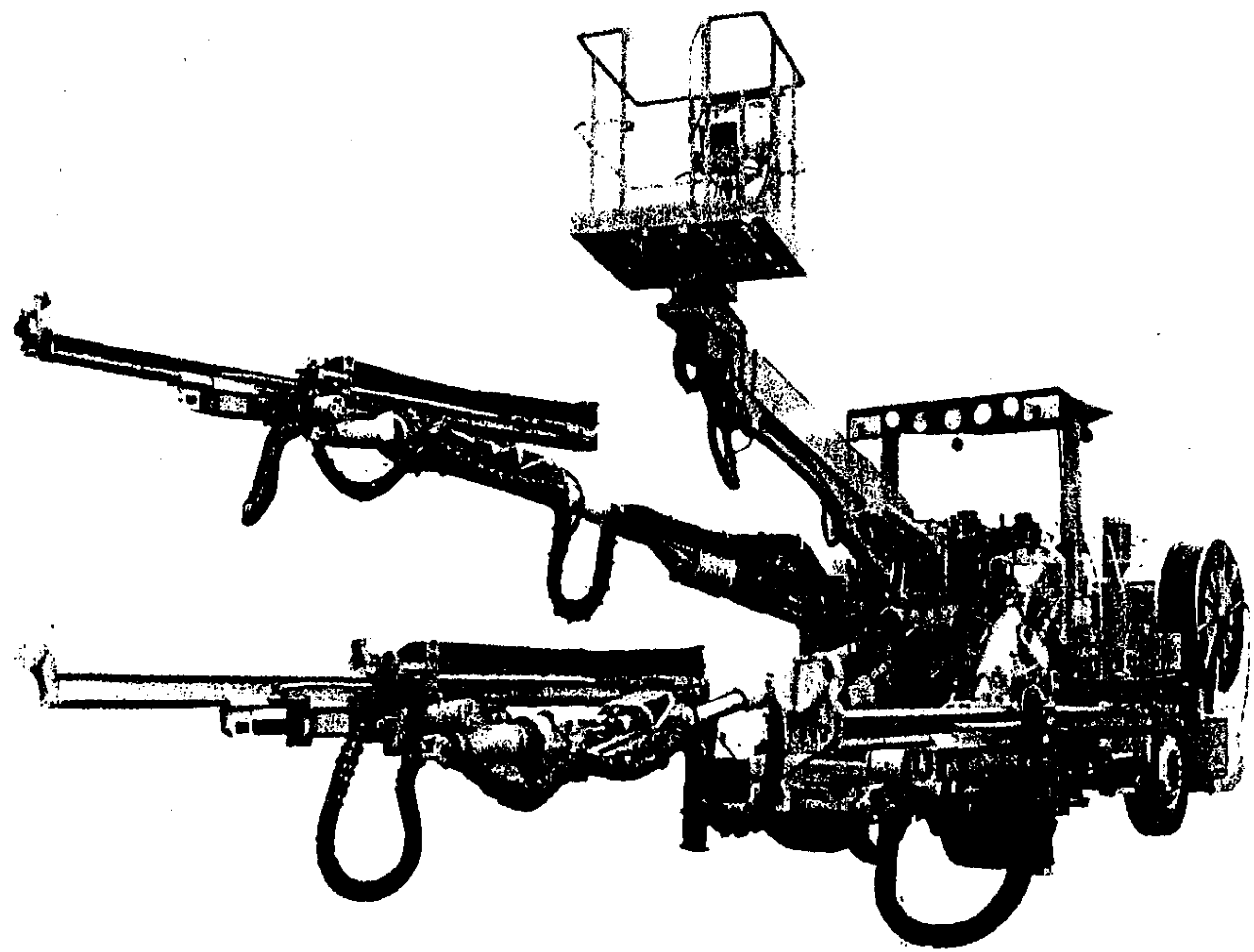
In most hard rock types, the Mobile miner is the cost competitive choice

Single heading development rates surpass those possible using conventional drill and blast techniques.

In most rock types, the excavation costs of the Mobile Miner are equal to or lower than drill and blast costs. Robbins will supply performance and excavation cost estimates for specific applications.

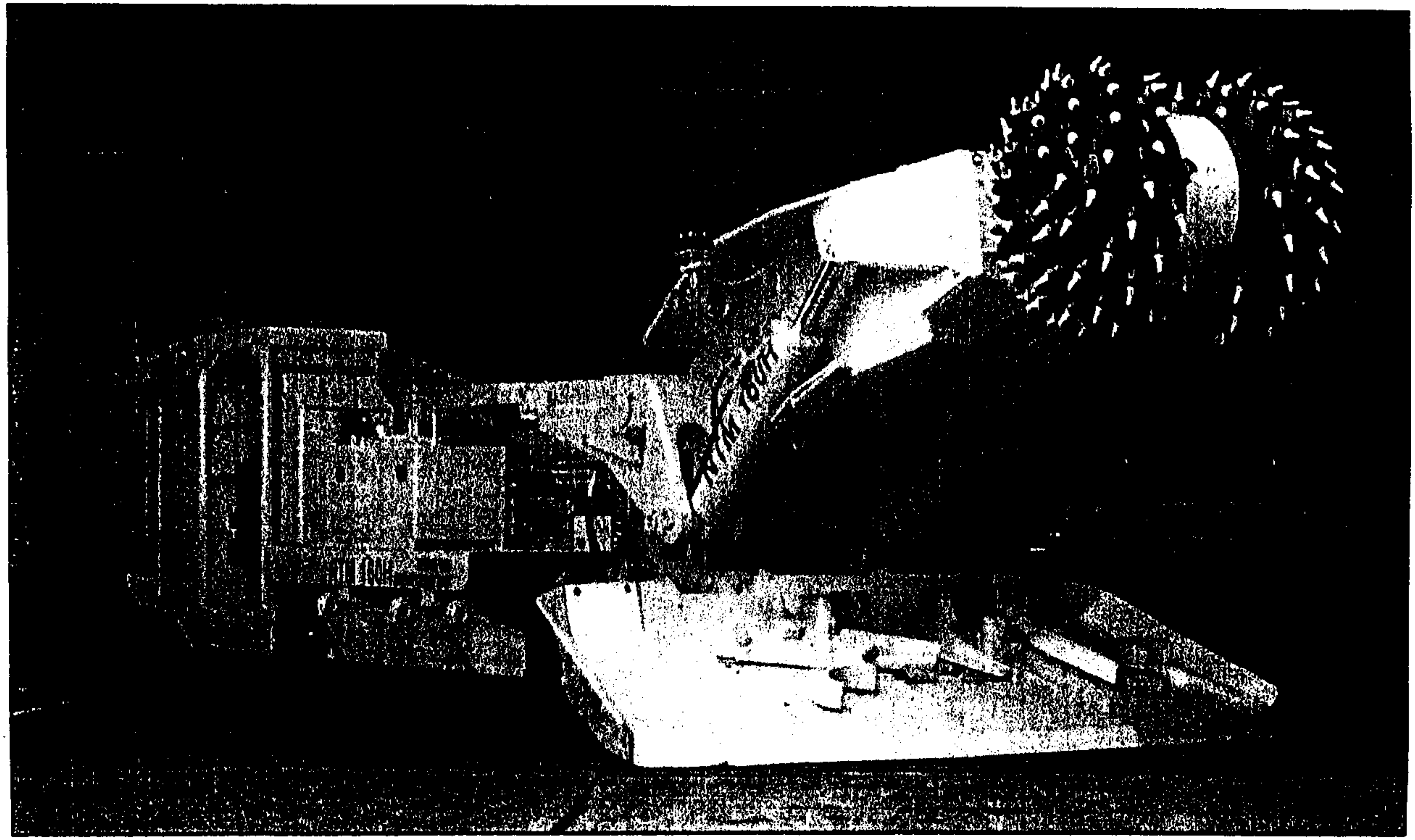
Rocket Boomer 353

Three-boom, heavy tunnelling rig for cross sections 20 - 100 m^2



42026-2

Twin Head Roadheader (Noell)



APPENDIX

COST ANALYSIS SPREADSHEET

Description

Sample Spreadsheet

Sample Chart

APPENDIX

COST ANALYSIS SPREADSHEET

Description

Sample Spreadsheet

Sample Chart

COST ANALYSIS SPREADSHEET

A computer spreadsheet file is provided with this report, the intention of which is to enable the user to quickly assess the effects on overall booster tunneling costs of variations in such parameters as tunneling advance rate, mucking and utility distances, labor usage, and the costs of various elements of the tunnel construction.

It is written in Microsoft Excel 97. The file is named "costanal.xls".

A sample printout of the spreadsheet is included in the appendix, plus a sample print of the cost distribution bar chart. Equipment, material, utility, labor, and other costs may be changed by the user. The costs currently indicated are for general guidance only and should be carefully reviewed before using the spreadsheet for input in major decisions. The spreadsheet is set up to forecast costs for tunnels of 8, 10, and 12 foot diameter. As distributed, the spreadsheet is in the "protected mode" so that only cells used for input (filled green) can be changed, however the user can override the protection to revise, change, or add to the spreadsheet as desired.

The spreadsheet calculates the costs for a tunnel of the length defined by the first input line, and assumes that one tunneling system is used for that length. If two systems are used (i.e. 17 km each), then the cost of the complete tunnel will be double the result. The administration costs are automatically reduced by 37.5 percent in this case, as it is assumed that one main administrative team would run two systems, with some slight increase required. It is obviously very difficult to exactly predict administrative labor costs accurately, and judgement is called for in this area. The lengths of the mucking and utility supply distances can be changed to assess the effects of using intermediate access shafts.

The spreadsheet is focussed on the costs related to the tunnel boring system and the construction of the horizontal tunnel itself. The total costs include construction of the access shafts and ramps, and surface facilities, consolidation grouitng, and overhead costs such as freight costs. These can be included in two miscellaneous categories. Additional costs that can be included are contractor overhead and profit margins, muck disposal, and an overall contingency factor. The costs shown on the current version of the spreadsheet are based on figures from the Kenny cost analysis, and again judgement is required to obtain realistic projections.

The bar chart shows totals for sub- and major categories. The values indicated on the bars do not include the overhead, profit, and contingency costs, but these are included in the overall cost and cost per meter summary. The basic input parameters are linked to the spreadsheet inputs. A chart is available for each tunnel diameter.

The cost of the tunnel invert and consolidation grouting is included in the basic tunneling cost, whereas in the Kenny cost estimate these costs are called out separately from the tunnel ring construction. Kenny is assuming that a slip formed invert is constructed after the tunnel boring is complete. The spreadsheet as currently configured assumes placement of invert segments concurrent with boring, but can be modified to incorporate slip forming costs and the effect on the overall schedule.

The cost breakdown structure in the spreadsheet and that in the Kenny estimate differ in some areas, and any comparisons must be made with care.

Description of Basic Input Items (excluding cost items in spreadsheet body)

Number of Tunneling Systems: Enter 1 or 2. It is assumed that if there are two, then each will bore 17 km.

Penetration Rate: Enter average penetration rate in meters per hour

Utilization: Enter overall utilization based on boring hours as a percentage of total 24 hour work days devoted to tunnel construction, not including system installation, demobilization, and major repair or geological accident down time.

Maximum mucking length: maximum transportation length, depending on number of access point to tunnel

Maximum utilities length: as in mucking length, depending on availability of intermediate access.

Train speed: supply train speed. Affects total time workers spend underground.

Work days per week: allows calculation of number of calendar weeks

Shift hours per day: allows calculation of underground work time (Note: overtime rates not currently included).

Commissioning period: number of days to install TBM system.

Demobilization period: number of days to remove TBM system, track, and mucking system.

Miscellaneous Extra Working Days: contingency for major downtime including breakdown and geological accidents.

Extra Administrative Time: additional time that administrative staff is on site for surface plant preparation, shaft construction, and tidy up at job finish.

Interest rate: used to compute cost of capital tied up in equipment.

Contingency Factor: factor to allow for estimating errors, major problems etc.

Contractor overhead and profit: use industry average markups.

TUNNELING COST REDUCTION STUDY

COST ANALYSIS

NUMBER OF TUNNELING SYSTEMS	1		
PENETRATION RATE	10	M/HR	I
UTILIZATION	40	%	
MAX MUCKING LENGTH	17,000	METERS	
MAX UTILITIES LENGTH	17,000	METERS	N
TRAIN SPEED	15	KM/HR	
WORK DAYS/WEEK	5	DAYS	P
SHIFT HOURS PER DAY	20	HOURS	
COMMISSIONING PERIOD	40	DAYS	
DEMOBILIZATION PERIOD	40	DAYS	U
MISCELLANEOUS EXTRA WORKING DAYS	50	DAYS	
EXTRA ADMINISTRATIVE TIME	12	MONTHS	
			T
INTEREST RATE	4.8	APR	
CONTINGENCY %	10	%	
CONTRACTOR O'HEAD & PROFIT %	20	%	
TUNNEL LENGTH	34,000	METRES	
NET ADVANCE RATE	4.0	M/HR	O
BORING HOURS	3,400	HOURS	U
WORK DAYS	484	DAYS	T
CALENDAR WEEKS (TUNNELING)	96	WEEKS	P
OVERALL DURATION	35.3	MONTHS	U
			T
AVERAGE TRAVEL TIME	2.3	HOURS	

COST SUMMARY CHART

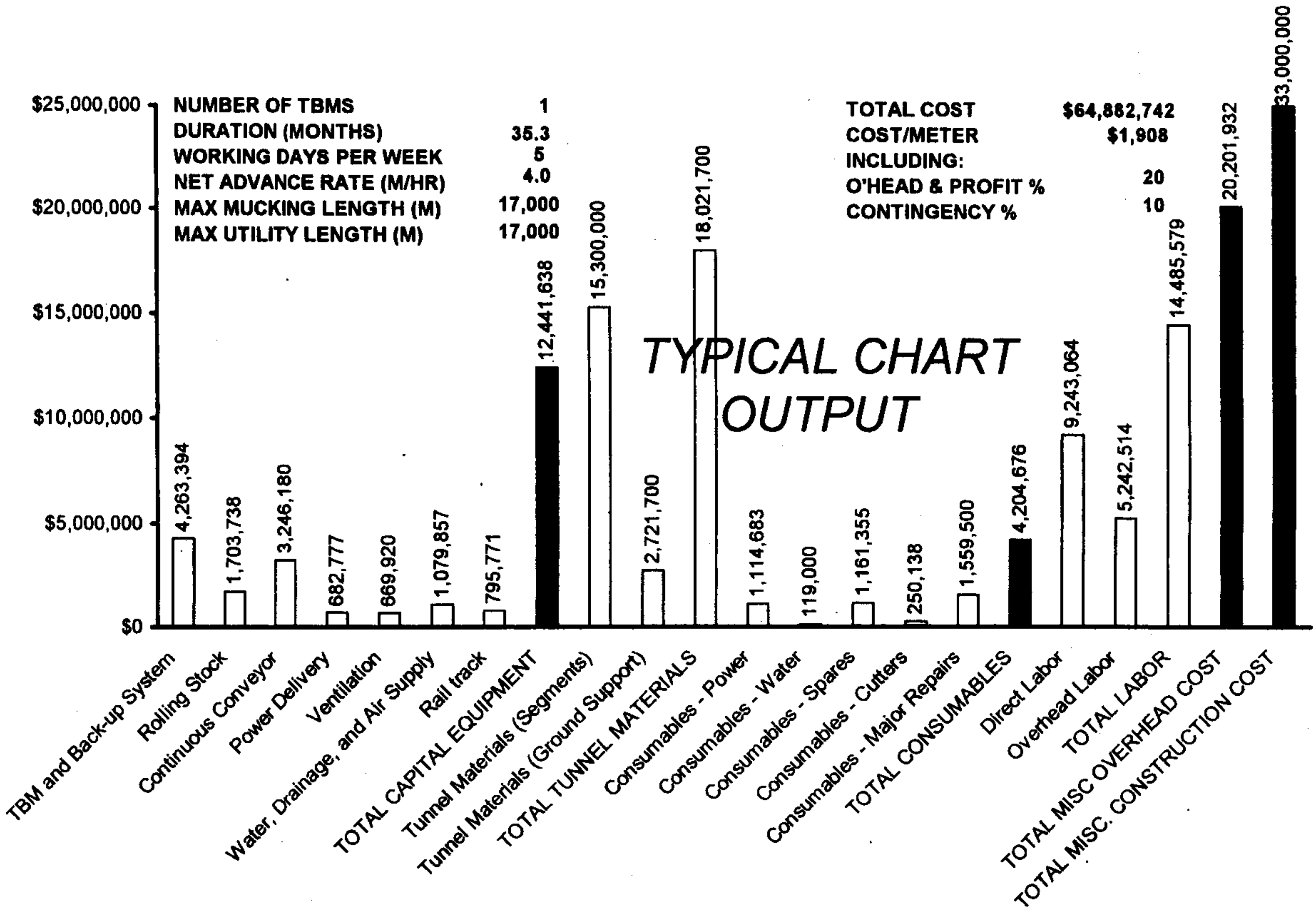
ITEM	8 FOOT			10 FOOT			12 FOOT		
	NEW	RESALE VALUE	COST	NEW	RESALE VALUE	COST	NEW	RESALE VALUE	COST
TBM and Back-up System	3,755,000	1,156,000	3,137,263	4,571,500	1,471,500	3,791,828	5,388,000	1,940,000	4,263,394
Rolling Stock	2,800,000	1,520,000	1,703,738	2,800,000	1,520,000	1,703,738	2,800,000	1,520,000	1,703,738
Continuous Conveyor	3,880,000	1,166,000	3,246,180	3,880,000	1,166,000	3,246,180	3,880,000	1,166,000	3,246,180
Power Delivery	545,000	160,000	467,478	545,000	160,000	467,478	732,000	160,000	682,777
Ventilation	748,000	308,000	612,765	867,000	425,000	630,774	901,000	425,000	669,920
Water, Drainage, and Air Supply	1,129,000.00	220,000.00	1,079,857.33	1,129,000.00	220,000.00	1,079,857.33	1,129,000.00	220,000.00	1,079,857
Rail track	765,000.00	85,000.00	795,771.35	765,000.00	85,000.00	795,771.35	765,000.00	85,000.00	795,771
TOTAL CAPITAL EQUIPMENT	13,622,000	4,643,000	11,043,064	14,557,500	5,047,500	11,715,927	15,595,000	5,516,000	12,441,638
Tunnel Materials (Segments)			8,500,000			10,200,000			15,300,000
Tunnel Materials (Ground Support)			2,721,700			2,721,700			2,721,700
TOTAL TUNNEL MATERIALS			11,221,700			12,921,700			18,021,700
Consumables - Power			791,683			995,683			1,114,683
Consumables - Water			85,000			102,000			119,000
Consumables - Spares			516,256			806,650			1,161,355
Consumables - Cutters			111,194			173,740			250,138
Consumables - Major Repairs			1,362,200			1,455,750			1,559,500
TOTAL CONSUMABLES			2,866,333			3,533,823			4,204,676
Direct Labor			8,429,664			9,243,064			9,243,064
Overhead Labor			5,242,514			5,242,514			5,242,514
TOTAL LABOR			13,672,179			14,485,579			$14,485,579
TOTAL MISC OVERHEAD COST			18,258,710			19,132,360			20,201,932
TOTAL MISC. CONSTRUCTION COST			27,000,000			30,000,000			33,000,000
TOTAL TUNNELING COST			38,803,265			42,656,730			49,153,593
INC.CONTINGENCY FACTOR			42,683,592			46,922,403			54,068,952
INC. CONTRACTOR OVERHEAD & PROFIT			$51,220,310			$56,306,883			$64,882,742
COST PER METER			$1,506			$1,656			$1,908

ITEM	8 FOOT			10 FOOT			12 FOOT		
	NEW	RES VALUE	COST	NEW	RES VALUE	COST	NEW	RES VALUE	COST
TUNNELING SYSTEM CAPITAL EQUIPMENT HAVING RESALE VALUE									
BASIC TBM	$2,500,000	$800,000	2,078,338	3,250,000	1,000,000	2,741,839	4,000,000	1,500,000	3,105,340
includes:									
Ring Beam Guide									
Cutter Handling Tools									
Operators Control Station									
ANCILLARY EQUIPMENT									
Roof Drills	200,000	30,000	200,267	200,000	30,000	200,267	200,000	30,000	200,267
Laser Target	150,000	100,000	72,700	150,000	100,000	72,700	150,000	100,000	72,700
BACKUP SYSTEM:									
includes:									
Structure	700,000	125,000	680,935	750,000	133,000	730,501	800,000	150,000	771,068
Scrubber	30,000	20,000	14,540	35,000	23,500	16,797	40,000	27,000	19,053
Scrubber Ducting	4,000	0	4,605	4,000	0	4,605	4,000	0	4,605
Duct Cassette	9,000	6,000	4,382	10,500	75,000	-62,911	12,000	8,000	5,816
Water Pump	12,000	3,000	10,816	12,000	3,000	10,816	12,000	3,000	10,816
Shotcrete System	50,000	37,000	20,567	50,000	37,000	20,567	50,000	37,000	20,567
Hoisting Equipment	20,000	10,000	13,027	20,000	10,000	13,027	20,000	10,000	13,027
Main Transformers	80,000	55,000	37,107	90,000	60,000	43,620	100,000	75,000	40,134
TOTAL TBM SYSTEM	3,756,000	1,186,000	3,137,263	4,571,500	1,471,500	3,791,828	5,388,000	1,940,000	4,263,394
ROLLING STOCK									
Number of sets	6			6			6		
Locomotives (each)	160,000	100,000		160,000	100,000		160,000	100,000	
Locomotive total cost	960,000	600,000	505,282	960,000	600,000	505,282	960,000	600,000	505,282
Supply Cars (one set)	300,000	150,000		300,000	150,000		300,000	150,000	
Supply Cars total cost	1,800,000	900,000	1,172,403	1,800,000	900,000	1,172,403	1,800,000	900,000	1,172,403
Personnel Cars	40,000	20,000	26,053	40,000	20,000	26,053	40,000	20,000	26,053
Muck Cars (one set)	0	0		0	0		0	0	
Muck Cars total cost	0	0	0	0	0	0	0	0	0
TOTAL ROLLING STOCK	2,800,000	1,520,000	1,703,738	2,800,000	1,520,000	1,703,738	2,800,000	1,520,000	1,703,738

CONTINUOUS CONVEYOR									
Conveyor max length	17,000			17,000			17,000		
Installation Station	120,000	50,000	88,160	120,000	50,000	88,160	120,000	50,000	88,160
Main Drive	95,000	65,000	44,377	95,000	65,000	44,377	95,000	65,000	44,377
Storage Unit	220,000	150,000	103,294	220,000	150,000	103,294	220,000	150,000	103,294
Belt (per metre)	37	0		37	0		37	0	
Belt cost	1,258,000	0	1,448,380	1,258,000	0	1,448,380	1,258,000	0	1,448,380
Idlers and Structure (per metre)	69	20		69	20		69	20	
Idler and Structure cost	1,173,000	340,000	1,010,516	1,173,000	340,000	1,010,516	1,173,000	340,000	1,010,516
Carrying Boosters (per 2500m)	95,000	60,000		95,000	60,000		95,000	60,000	
Booster cost	570,000	360,000	296,261	570,000	360,000	296,261	570,000	360,000	296,261
Return Boosters (per 5000m)	80,000	50,000		80,000	50,000		80,000	50,000	
Booster cost	240,000	150,000	126,320	240,000	150,000	126,320	240,000	150,000	126,320
Signal communication	85,000	55,000	42,863	85,000	55,000	42,863	85,000	55,000	42,863
Emergency stop system (per metre)	7	3		7	3		7	3	
Emergency system cost	119,000	51,000	86,009	119,000	51,000	86,009	119,000	51,000	86,009
TOTAL CONVEYOR COST	3,880,000	1,166,000	3,246,180	3,880,000	1,166,000	3,246,180	3,880,000	1,166,000	3,246,180
POWER SUPPLY									
Max power cable length	17,000			17,000			17,000		
Power Cable (per metre)	25	5		25	5		36	5	
Power Cable cost	425,000	85,000	404,317	425,000	85,000	404,317	612,000	85,000	619,617
Booster Transformers (each)	40,000	25,000		40,000	25,000		40,000	25,000	
Boost Trans Spacing	5,000			5,000			5,000		
Number Booster Transformers	3			3			3		
Booster Transformers	120,000	75,000	63,160	120,000	75,000	63,160	120,000	75,000	63,160
TOTAL POWER SUPPLY EQUIPMENT	546,000	160,000	467,478	546,000	160,000	467,478	732,000	160,000	682,777
MAIN VENTILATION									
Max ducting length	17,000			17,000			17,000		
Ducting (per metre)	9	0		11	0		13	0	
Ducting Cost	153,000	0	176,154	187,000	0	215,300	221,000	0	254,445
Booster Fans (per 1000 metres)	35,000	18,000		40,000	25,000		40,000	25,000	
Booster fan cost	595,000	306,000	379,044	680,000	425,000	357,908	680,000	425,000	357,908
Misc.	50,000	0	57,567	50,000	0	57,567	50,000	0	57,567
TOTAL TUNNEL VENTILATION COST	748,000	306,000	612,765	867,000	425,000	630,774	901,000	425,000	689,920
WATER, DRAINAGE, & AIR SUPPLY									
Water supply and drainage max length	17,000			17,000			17,000		
WATER SUPPLY									
Piping cost (per metre)	12	3		12	3		12	3	
Piping cost	204,000	51,000	183,872	204,000	51,000	183,872	204,000	51,000	183,872
Booster Pumps	60,000	20,000	49,080	60,000	20,000	49,080	60,000	20,000	49,080
Misc	50,000	0	57,567	50,000	0	57,567	50,000	0	57,567
DRAINAGE SYSTEM									
Piping (per metre)	22	3		22	3		22	3	
Piping cost	374,000	51,000	379,599	374,000	51,000	379,599	374,000	51,000	379,599
Booster Pumps	60,000	30,000	39,080	60,000	30,000	39,080	60,000	30,000	39,080
Misc	50,000	0	57,567	50,000	0	57,567	50,000	0	57,567
AIR SUPPLY									
Piping (per metre)	18	4		18	4		18	4	
Piping cost	306,000	68,000	284,309	306,000	68,000	284,309	306,000	68,000	284,309
Misc	25,000	0	28,783	25,000	0	28,783	25,000	0	28,783
TOTAL WATER, DRAINAGE, AND AIR	1,129,000	220,000	1,079,867	1,129,000	220,000	1,079,867	1,129,000	220,000	1,079,867
RAIL SYSTEM									
Max track length	17,000			17,000			17,000		
Rail including fittings (per metre)	45	5		45	5		45	5	
Rail cost	765,000	85,000	795,771	765,000	85,000	795,771	765,000	85,000	795,771
TOTAL RAIL TRACK COST	$765,000	$85,000	$795,771	$765,000	$85,000	$795,771	$765,000	$85,000	$795,771
TOTAL IN-TUNNEL CAPITAL EQUIPMENT	$13,522,000	$4,643,000	$11,043,064	$14,557,500	$5,047,500	$11,715,627	$15,595,000	$5,516,000	$12,441,638
TUNNEL MATERIALS									
Invert Segment (per metre)			250			300			450
TOTAL SEGMENT COST			8,500,000			10,200,000			15,300,000
TUNNEL SUPPORT									
Class I Length (percent)			46.5			46.5			46.5
Class II Length (percent)			46.5			46.5			46.5
Class III Length (percent)			6.0			6.0			6.0
Class IV Length (percent)			1.0			1.0			1.0
Class I cost per meter			75			75			75
Class II cost per meter			75			75			75
Class III cost per meter			130			130			130
Class IV cost per meter			250			250			250
Overall cost in Class I			1,185,750			1,185,750			1,185,750
Overall cost in Class II			1,185,750			1,185,750			1,185,750
Overall cost in Class III			265,200			265,200			265,200
Overall cost in Class IV			85,000			85,000			85,000
TOTAL SUPPORT MATERIAL COST			2,721,700			2,721,700			2,721,700
TOTAL TUNNEL MATERIALS			11,221,700			12,921,700			18,021,700
CONSUMABLE ITEMS & REPAIRS									
POWER COST									
Average demand per boring hour kW			900			1,150			1,250
Continuous conveyor power			250			300			375
Misc continuous consumption			100			100			100
Power cost			0.20			0.20			0.20
TOTAL POWER COST			791,683			985,683			1,114,683
WATER COST									
Average demand per metre (liters)			50			60			70
Water cost per liter			0.05			0.05			0.05
TOTAL WATER COST			85,000			102,000			119,000

MINOR SPARE PARTS									
Cost per cubic metre (TBM)			1.75			1.75			1.75
Cost per cubic metre (Back-up)			0.50			0.50			0.50
Cost per cubic metre (Conveyor)			0.50			0.50			0.50
Cost per cubic metre (Rolling stock)			0.50			0.50			0.50
TOTAL MINOR SPARES COST			516,256			806,650			1,161,366
CUTTERS									
Cost per cubic meter			0.70			0.70			0.70
TOTAL CUTTER COST			111,194			173,740			250,138
MAJOR REPAIR CONTINGENCY									
Contingency Factor on Capital Cost %			10			10			10
CONTINGENCY COST			1,382,200			1,456,750			1,559,500
TOTAL CONSUMABLES & REPAIRS			2,866,333			3,633,823			4,204,676
<u>DIRECT LABOR</u>									
SHIFT BOSS			653,302			653,302			653,302
Hourly rate (inc o/h)		55.00			55.00			55.00	
TBM OPERATOR			534,520			534,520			534,520
Hourly rate (inc o/h)		45.00			45.00			45.00	
TECHNICIANS			1,069,040			1,069,040			1,069,040
Number		2			2			2	
Hourly rate (inc o/h)		45.00			45.00			45.00	
LABORERS - IN TUNNEL			1,900,516			1,900,516			1,900,516
Number		4			4			4	
Hourly rate (inc o/h)		40.00			40.00			40.00	
LABORERS - SURFACE			1,452,500			1,452,500			1,452,500
Number		4			4			4	
Hourly rate (inc o/h)		37.50			37.50			37.50	
LOCO DRIVERS			1,626,800			2,440,200			2,440,200
Number		4			6			6	
Hourly rate (inc o/h)		42.00			42.00			42.00	
MAINTENANCE CREW			1,192,987			1,192,987			1,192,987
Number		6			6			6	
Hourly rate (inc o/h)		40.00			40.00			40.00	
TOTAL DIRECT LABOR			8,429,664			9,243,064			9,243,064
<u>OVERHEAD LABOR</u>									
PROJ MGR			418,286			418,286			418,286
Monthly rate (inc o/h)		12,000			12,000			12,000	
TUNNEL SUPERINTENDENT			366,000			366,000			366,000
Monthly rate (inc o/h)		10,500			10,500			10,500	
EQUIPMENT SUPERINTENDENT			366,000			366,000			366,000
Monthly rate (inc o/h)		10,500			10,500			10,500	
MASTER MECHANIC			400,857			400,857			400,857
Monthly rate (inc o/h)		11,500			11,500			11,500	
SAFETY MANAGER			261,429			261,429			261,429
Monthly rate (inc o/h)		7,500			7,500			7,500	
PROJ ENGR			292,800			292,800			292,800
Monthly rate (inc o/h)		8,400			8,400			8,400	
OFFICE ENGINEER			261,429			261,429			261,429
Monthly rate (inc o/h)		7,500			7,500			7,500	
TUNNEL ENGINEERS			958,571			958,571			958,571
Number		5			5			5	
Monthly rate (inc o/h)		5,500			5,500			5,500	
SAFETY ENGINEER			418,286			418,286			418,286
Number		2			2			2	
Monthly rate (inc o/h)		6,000			6,000			6,000	
COST/SCHEDULER			244,000			244,000			244,000
Monthly rate (inc o/h)		7,000			7,000			7,000	
CLERICAL			1,254,857			1,254,857			1,254,857
Number		6			6			6	
Monthly rate (inc o/h)		6,000			6,000			6,000	
TOTAL OVERHEAD LABOR			5,242,514			5,242,514			5,242,514
TOTAL LABOR			13,672,179			14,485,579			14,485,579
<u>MISC. OVERHEAD COSTS</u>									
INBOUND FREIGHT			200,000			200,000			200,000
INSURANCE & TAXES			4,000,000			4,000,000			4,000,000
MUCK DISPOSAL			1,556,710			2,432,360			3,501,932
Disposal cost $ per cu.meter		9.80			9.80			9.80	
SURFACE PLANT AND OFFICES			12,500,000			12,500,000			12,500,000
TOTAL MISC OVERHEAD COSTS			18,256,710			19,132,360			20,201,932
<u>MISC. CONSTRUCTION COSTS</u>									
TOTAL GROUTING COST			11,000,000			13,000,000			15,000,000
STARTER TUNNEL CONSTRUCTION			7,000,000			8,000,000			9,000,000
SHAFT CONSTRUCTION			8,500,000			8,500,000			8,500,000
SHAFT MUCKING SYSTEMS			500,000			500,000			500,000
TOTAL MISC. CONSTRUCTION COSTS			27,000,000			30,000,000			33,000,000

TUNNELING COST REDUCTION STUDY



TUNNELING COST DISTRIBUTION - 12 FOOT DIAMETER

TUNNELING COST REDUCTION STUDY

COST ANALYSIS

NUMBER OF TUNNELING SYSTEMS	[illegible]	
PENETRATION RATE	[illegible]	M/HR
UTILIZATION	[illegible]	%
MAX MUCKING LENGTH	17,[illegible]	METERS
MAX UTILITIES LENGTH	17,[illegible]	METERS
TRAIN SPEED	[illegible]	KM/HR
WORK DAYS/WEEK	[illegible]	DAYS
SHIFT HOURS PER DAY	[illegible]	HOURS
COMMISSIONING PERIOD	[illegible]	DAYS
DEMOBILIZATION PERIOD	[illegible]	DAYS
MISCELLANEOUS EXTRA WORKING DAYS	[illegible]	DAYS
EXTRA ADMINISTRATIVE TIME	[illegible]	MONTHS
INTEREST RATE	[illegible]	APR
CONTINGENCY %	[illegible]	%
CONTRACTOR O'HEAD & PROFIT %	[illegible]	%
TUNNEL LENGTH	[illegible]	METRES
NET ADVANCE RATE	[illegible]	M/HR
BORING HOURS	[illegible]	HOURS
WORK DAYS	[illegible]	DAYS
CALENDAR WEEKS (TUNNELING)	[illegible]	WEEKS
OVERALL DURATION	[illegible]	MONTHS
AVERAGE TRAVEL TIME	[illegible]	HOURS

COST SUMMARY CHART

ITEM	8 FOOT			10 FOOT			12 FOOT		
	NEW	RESALE VALUE	COST	NEW	RESALE VALUE	COST	NEW	RESALE VALUE	COST
TBM and Back-up System	3,755,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Rolling Stock	2,800,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1,703,728
Continuous Conveyor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Power Delivery	545,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ventilation	748,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Water, Drainage, and Air Supply	1,128,000.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1,079,857
Rail track	785,000.00	85,000.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	785,771
TOTAL CAPITAL EQUIPMENT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tunnel Materials (Segments)			[illegible]			[illegible]			15,300,000
Tunnel Materials (Ground Support)			2,721,700			[illegible]			2,721,700
TOTAL TUNNEL MATERIALS			[illegible]			[illegible]			[illegible]
Consumables - Power			[illegible]			[illegible]			[illegible]
Consumables - Water			[illegible]			[illegible]			119,000
Consumables - Spares			[illegible]			[illegible]			[illegible]
Consumables - Cutters			[illegible]			[illegible]			[illegible]
Consumables - Major Repairs			[illegible]			[illegible]			[illegible]
TOTAL CONSUMABLES			[illegible]			[illegible]			[illegible]
Direct Labor			[illegible]			[illegible]			[illegible]
Overhead Labor			[illegible]			[illegible]			5,242,514
TOTAL LABOR			[illegible]			[illegible]			[illegible]
TOTAL MISC OVERHEAD COST			[illegible]			[illegible]			[illegible]
TOTAL MISC. CONSTRUCTION COST			[illegible]			[illegible]			[illegible]
TOTAL TUNNELING COST			[illegible]			[illegible]			[illegible]
INC. CONTINGENCY FACTOR			[illegible]			[illegible]			[illegible]
INC. CONTRACTOR OVERHEAD & PROFIT			[illegible]			[illegible]			[illegible]
COST PER METER			[illegible]			[illegible]			[illegible]

ITEM	NEW	8 FOOT RES VALUE	COST	NEW	10 FOOT RES VALUE	COST	NEW	12 FOOT RES VALUE	COST
TUNNELING SYSTEM CAPITAL EQUIPMENT HAVING RESALE VALUE									
BASIC TBM	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
includes:									
Ring Beam Guide									
Cutter Handling Tools									
Operators Control Station									
ANCILLARY EQUIPMENT									
Roof Drills	200,000	[illegible]	[illegible]	200,000	30,000	[illegible]	[illegible]	[illegible]	[illegible]
Laser Target	[illegible]	[illegible]	[illegible]	[illegible]	100,000	[illegible]	[illegible]	[illegible]	72,700
BACKUP SYSTEM:									
includes:									
Structure	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Scrubber	30,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Scrubber Ducting	4,000	[illegible]	[illegible]	4,000	0	[illegible]	[illegible]	[illegible]	[illegible]
Duct Cassette	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Water Pump	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Shotcrete System	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Hoisting Equipment	20,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Main Transformers	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL TBM SYSTEM	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ROLLING STOCK									
Number of sets	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Locomotives (each)	160,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Locomotive total cost	960,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Supply Cars (one set)	200,000	[illegible]	[illegible]	[illegible]	160,000	[illegible]	[illegible]	[illegible]	[illegible]
Supply Cars total cost	1,600,000	[illegible]	[illegible]	[illegible]	[illegible]	1,172,400	[illegible]	[illegible]	1,172,400

Personnel Cars	40,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Muck Cars (one set)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Muck Cars total cost	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
TOTAL ROLLING STOCK	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CONTINUOUS CONVEYOR										
Conveyor max length	17,000	[illegible]	[illegible]	17,000	[illegible]	[illegible]	17,000	[illegible]	[illegible]	[illegible]
Installation Station	120,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	80,000	[illegible]
Main Drive	85,000	85,000	[illegible]	[illegible]	[illegible]	44,577	[illegible]	[illegible]	44,577
Storage Unit	220,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Belt (per metre)	37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Belt cost	1,258,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Idlers and Structure (per metre)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Idler and Structure cost	1,173,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Carrying Boosters (per 2500m)	85,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Booster cost	670,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Return Boosters (per 5000m)	80,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Booster cost	240,000	160,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Signal communication	85,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Emergency stop system (per metre)	7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Emergency system cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL CONVEYOR COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
POWER SUPPLY										
Max power cable length	17,000	[illegible]	[illegible]	17,000	[illegible]	[illegible]	17,000	[illegible]	[illegible]
Power Cable (per metre)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Power Cable cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	610,817
Booster Transformers (each)	40,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Boost Trans Spacing	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Number Booster Transformers	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Booster Transformers	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL POWER SUPPLY EQUIPMENT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MAIN VENTILATION										
Max ducting length	17,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ducting (per metre)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ducting Cost	153,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Booster Fans (per 1000 metres)	35,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Booster fan cost	105,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Misc.	50,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL TUNNEL VENTILATION COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WATER DRAINAGE, & AIR SUPPLY										
Water supply and drainage max length	17,000	[illegible]	[illegible]	17,000	[illegible]	[illegible]	17,000	[illegible]	[illegible]
WATER SUPPLY										
Piping cost (per metre)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Piping cost	204,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Booster Pumps	80,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Misc	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DRAINAGE SYSTEM										
Piping (per metre)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Piping cost	374,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Booster Pumps	80,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Misc	50,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AIR SUPPLY										
Piping (per metre)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Piping cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Misc	35,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL WATER, DRAINAGE, AND AIR	1,129,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
RAIL SYSTEM										
Max track length	17,000	[illegible]	[illegible]	17,000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Rail including fittings (per metre)	45	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Rail cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL RAIL TRACK COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL IN-TUNNEL CAPITAL EQUIPMENT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TUNNEL MATERIALS										
Invert Segment (per metre)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	450
TOTAL SEGMENT COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TUNNEL SUPPORT										
Class I Length (percent)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Class II Length (percent)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Class III Length (percent)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.0
Class IV Length (percent)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.0
Class I cost per meter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	75
Class II cost per meter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	75
Class III cost per meter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	130
Class IV cost per meter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	250
Overall cost in Class I	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Overall cost in Class II	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Overall cost in Class III	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	285,200
Overall cost in Class IV	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	65,000
TOTAL SUPPORT MATERIAL COST			[illegible]			[illegible]			[illegible]
TOTAL TUNNEL MATERIALS			[illegible]			[illegible]			[illegible]
CONSUMABLE ITEMS & REPAIRS										

POWER COST									
Average demand per boring hour kW	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Continuous conveyor power	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Misc continuous consumption	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Power cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL POWER COST			[illegible]			[illegible]			[illegible]
WATER COST									
Average demand per metre (liters)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Water cost per liter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL WATER COST			[illegible]			[illegible]			[illegible]
MINOR SPARE PARTS									
Cost per cubic metre (TBM)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cost per cubic metre (Back-up)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cost per cubic metre (Conveyor)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cost per cubic metre (Rolling stock)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL MINOR SPARES COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CUTTERS									
Cost per cubic meter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL CUTTER COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MAJOR REPAIR CONTINGENCY									
Contingency Factor on Capital Cost %	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CONTINGENCY COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL CONSUMABLES & REPAIRS			[illegible]			[illegible]			[illegible]
DIRECT LABOR									
SHIFT BOSS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Hourly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
TBM OPERATOR	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Hourly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
TECHNICIANS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Number	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
Hourly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
LABORERS - IN TUNNEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Number	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
Hourly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
LABORERS - SURFACE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Number	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
Hourly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
LOCO DRIVERS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Number	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
Hourly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
MAINTENANCE CREW	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Number	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
Hourly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
TOTAL DIRECT LABOR			[illegible]			[illegible]			[illegible]
OVERHEAD LABOR									
PROJ MGR	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
TUNNEL SUPERINTENDENT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
EQUIPMENT SUPERINTENDENT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
MASTER MECHANIC	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
SAFETY MANAGER	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
PROJ ENGR	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
OFFICE ENGINEER	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
TUNNEL ENGINEERS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Number	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
SAFETY ENGINEER	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Number	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
COST/SCHEDULER	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
CLERICAL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Number	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
Monthly rate (inc o/h)	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
TOTAL OVERHEAD LABOR	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL LABOR			[illegible]			[illegible]			[illegible]
MISC. OVERHEAD COSTS									
INBOUND FREIGHT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INSURANCE & TAXES	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MUCK DISPOSAL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Disposal cost $ per cu.meter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SURFACE PLANT AND OFFICES	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL MISC OVERHEAD COSTS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MISC. CONSTRUCTION COSTS									
TOTAL GROUTING COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
STARTER TUNNEL CONSTRUCTION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SHAFT CONSTRUCTION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SHAFT MUCKING SYSTEMS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL MISC. CONSTRUCTION COSTS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]