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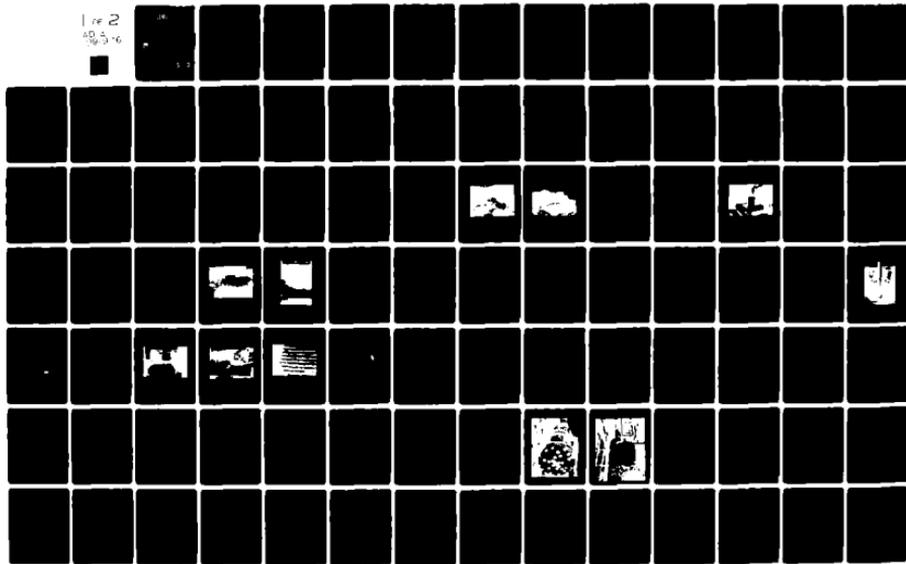
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TUNNEL BORING MACHINE TECHNOLOGY FOR A DEEPLY BASED MISSILE SYSTEM

Volume I of II
Application Feasibility

Part 1 of 2

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August 1980

Final Report

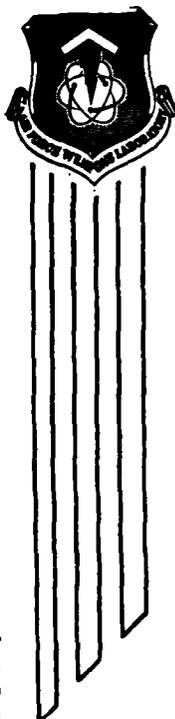
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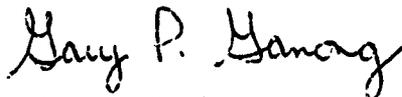
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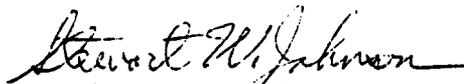


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18. SUPPLEMENTARY NOTES This report consists of two volumes: Volume I, Application Feasibility, and Volume II, State-of-the-Art Review. Volume I is divided into two parts. Part 1 consists of the front matter and text pages 1-108. Part 2 consists of text pages 109-198 and the distribution list.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Tunneling Underground Structures Rock Mechanics		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Technical feasibility and cost studies were made for a deep-based missile (DBM) tunnel system (Mesa concept) by means of tunnel boring machines (TBMs), along with designing an egress machine for post-attack tunneling through approxi- mately 2,500 feet of probably unstable rock to the rubble zone. Currently, available designs of TBMs are readily adaptable for the conven- tional excavation in geologic environment considered suitable for DBM siting. Most, if not all, of the tunnel sections in the rocks of anticipated structure (Continued)		

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and strength will require support varying from simple rock bolting to concrete segments.

Current (1979) costs for similar tunnels (Chicago) vary from \$600 to \$800 per linear foot of tunnel, while the estimated costs for the DBM tunnels average as high as \$1,600 per foot because of the greater depths, weaker rock, longer tunnels, possible remoteness geographically, and other related factors.

Two concepts for egress machines have been proposed by the Robbins and Jarva companies.

The details of use of geotechnical data are given in Appendix A and were qualitatively for estimates of support requirements and costs. The only calculation that could be made based upon available data was the assumption that squeezing ground would occur if the stress concentration at the ribs of the tunnels exceeds the unconfined compressive strength. Average conditions assumed for the tunnel calculations in the COSTUN program automatically include the effects of rock quality designation (RQD), etc.

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PREFACE

The goal of this study has been to realistically evaluate the feasibility of using tunnel boring machines for a military weapon system, both with respect to creating the tunnel complex and for egressing from a deeply buried missile complex. Although the evaluation was performed primarily by the Earth Mechanics Institute of the Colorado School of Mines, input on machine design and tunneling costs was obtained from two machine manufacturers and one construction firm. The tunnel boring machine manufacturers were The Robbins Company, Seattle, Washington, and Jarva Inc, Solon, Ohio, while the construction firm was Morrison Knudsen, Boise, Idaho.

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CHAPTER 1

INTRODUCTION

This research project was carried out as a detailed feasibility study of four factors to evaluate the performance of tunnel boring machines (TBMs): (1) their capabilities, (2) limitations, (3) adaptability, and (4) cost effectiveness for (a) conventional excavation for deploying a deep-based missile system, and (b) excavation of post-attack egress openings to, but not within, the rubble zone of talus slopes or craters.

The two missions to be performed by TBMs are the excavation of 480 km of 5-meter diameter tunnels by conventional tunnel boring methods in a geologic environment consisting largely of sandstone and associated rocks, and the excavation of post-attack egress openings by modified machines in the same media to the rubble zone. The types of TBMs required to perform these two different modes of excavation will have some elements in common and other elements which are quite different from both a technical and a logistic point of view.

The technical elements primarily include factors in machine design, the interaction at the rock-machine interface, control and guidance, muck handling, cutter replacement, machine repairs, evaluation of site geology, ventilation, and similar items that require skilled professionals and technicians to install, operate, and maintain.

The logistics include the management of personnel, and keeping power supplies, tools, repair parts, utilities, rock support, muck removal equipment, and similar items available. Conventional tunneling will require long supply lines and extended, continuous operation. Egress excavation will be limited to local supplies and will involve only short term operations at a local underground site which is isolated from the surface.

A comparison of the overall problems of the two modes of excavation can be analyzed with respect to the technical requirements of the operations and the logistic environments within which excavation operations must be carried out. In the conventional excavation, the restrictions on operations are relatively flexible. For egress excavation, the restrictions are most severe, and flexibility is practically zero. Most of the pertinent factors for conventional operation have been described in the literature (Tables 1 & 2), but some of these will be markedly different for egress operations.

Capital costs for conventional TBM excavation are of major consideration, both with respect to the cost per machine and the total project. However, for the egress tunnel boring machines (ETBMs), cost should be secondary to reliability, simplicity, and penetration rate.

A summary of the state of the art in tunnel boring was made (see Volume II) to serve as a basis for determining the approaches to the solutions of the problems associated with the excavation for a deep-based missile (DBM) and egress operations.

The basic principles of tunnel excavation given in a recent report (Ref. 1) have been abstracted in detail and are included in Appendix A of this volume. The engineering principles outlined therein furnish a representative basis for determining the feasibility and cost of tunneling for different site conditions.

-
1. Golder Associates & J.F. MacLaren, Ltd., "Tunneling Technology - An Appraisal of the State of the Art for Application to Transit Systems," Ontario Ministry of Transportation and Communication, May 1976.

TABLE 1
TECHNICAL REQUIREMENTS

Technical Factors	TBM	ETBM
1. Machine design to fit variable site conditions	Flexible for variable geological conditions	Designed for local site(s) of known geology
2. Machine construction to allow for changing conditions	Flexible for variable geological conditions	Limited flexibility, no machine changes
3. Change in design or operation to meet local conditions	Desirable for extensive excavation	Very limited for short operation
4. Changing cutters	Required for continued operation	Limited or no changes permitted
5. Repair & maintenance	As required	Limited by availability of parts and skill of personnel
6. Geological and engineering assistance	Available at all times	Not available
7. Simplified operation	Desirable but not required	Required because of limited skill of personnel
8. Ease of assembling and disassembling	Desirable but not required	Desirable but not required
9. Mobility	Desirable	Required for multiple opening excavation
10. Rate of penetration	Required to keep costs down	Required for military tactical reasons
11. Rate of advance	Required to keep costs down	Required for military tactical reasons
12. Energy requirements	Low as possible for economic reasons	Low as possible because of limited resources
13. Operation on curves	Desirable with minimum delay	Probably not required
14. Disposal of machine	Used until amortized or worn out	Must be moved to clear egress
15. Adapt to effects of attack	Not required	Machine adapted to excavate in damaged tunnels

TABLE 1 (Cont'd.)

Technical Factors	TBM	ETBM
16. Muck removal system	Required	Required
17. Power source	Required	Required - local

TABLE 2
LOGISTIC REQUIREMENTS

Logistic Factors	TBM	ETBM
1. Utilities		
a. Power	Supplied from civilian sources	Supplied from limited local sources
b. Ventilation	Conventional by vent line to outside	From local tunnel air or by drill hole to outside
c. Compressed air	Conventional pipe line	Local compressor if needed
d. Track	Conventional	Local only
e. Light	Conventional	Local source
2. Labor	Trained and skilled for operation and maintenance	Limited training and skills of military personnel
3. Supplies	Conventional	Local only
4. Repair parts	Conventional	Local only
5. Management	Conventional	Local military
6. Muck disposal	Conventional - possibly by extensive conveyor system	To existing underground space or outside through drill hole
7. Maintenance	Conventional	Local only with available parts and personnel

RESEARCH PROGRAM

The research effort dealt with the tasks as given in the Statement of Work, i.e., analysis and evaluation of the following as they affect the proposed DBM system and egress to the rubble zone.

1. TBM characteristics, capabilities, and limitations
2. TBM tunneling variables
3. TBM post-attack egress
4. Laboratory testing of rock properties for boreability to predict rates of penetration, rates of advance, and tunneling costs

Expertise and past experience of the research staff at the Colorado School of Mines (CSM) together with that of manufacturers, consultants, and contractors constituted the basic team for completion of the tasks described below, and this effort included a further detailed survey of literature, a compilation of additional data and information from TBM projects, and technical input from machine manufacturers, contractors, and consultants. This information, together with the results of laboratory tests and data on field geological conditions expected, specified required characteristics that were developed for (1) conventional, and (2) egress machines.

Cost effectiveness studies were made through analysis of laboratory cutting results and cost information from similar completed tunneling projects utilizing a computer program to determine cost projections for estimated percentages of good, medium, and bad ground. Projection of future costs have also taken into account the escalation of tunnel costs, plus the effects of inflation and the reduction of costs due to projected technological improvements. Based on the review of important phases, other cost studies were made by consultants and machine manufacturers of tunnel-

ing described in the report. Approaches to the accomplishment of the research objectives were carried out as follows.

APPROACHES

General

The research team at CSM served as the working nucleus of the task force in a cooperative effort with machine manufacturers, equipment users, tunnel owners, contractors, and consultants to give a balanced technical effort.

A complete literature survey was made and technical discussions were held with all members of the research team. These discussions provided first-hand knowledge of the specific background information and research and analysis that needed to be undertaken for determination of the *feasibility and costs of constructing the proposed tunnel network*

The laboratory testing phase consisted of obtaining first the mechanical cutting characteristics of rock obtained from a possible site with emphasis on cutter spacing, thrust, and penetration. Estimates of cutter wear were made by means of abrasiveness measurement methods. Cutters with artificial wear surfaces were tested to determine the reduction in performance due to wear. Based on these results, guidelines were established for a replacement schedule of dull cutters to balance the cost of cutter changes against the reduction of machine penetration due to cutter wear. The laboratory results were used with field conditions by incorporating the effects of geology, including joints, bedding, moisture, etc., which were based upon past experience with the effect of field geological features on rock boreability. Concurrent with laboratory cutting experimentation, rock cores were tested to determine the mechanical properties required for employing the predictor equations which have been developed in previous re-

search. The results of laboratory cutting tests and the predictor equations then served as the basis for recommendations on the most effective cutter spacing, cutter type, expected penetration rates, and cutter loads to be used in conjunction with overall machine design parameters.

A second phase of the laboratory investigation involved the application of low pressure, low volume water jets to assist mechanical cutting. Past research in this area has shown very promising results, and a combined water jet mechanical cutting system was found to be effective for use in conventional tunnel boring.

Based on laboratory findings and assembled information from past tunneling projects, cost effectiveness studies were completed. Further future costs also included considering effects of inflation and cost reductions due to technological improvements. Following is a breakdown and discussion of each task.

TASK I - TBM Characteristics, Capabilities, and Limitations

a. TBM Design and DBM System

Analysis of the differences and similarities of the requirements for the design and operation of TBMs for conventional excavation and egress excavation machine (Tables 1 & 2) indicates that a number of the elements are critical for both systems. The major differences are brought about because of the drastic contrast between the operation conditions for conventional vs urgent egress excavation. ..

One major question involved the possibility of utilizing the same machine for both categories of excavation. It appeared that important changes would be required in basic machine design if this is to be done. Although most of the features that are required for the ETBM would enhance the excavation operations of the TBM, two different types of machines may be required.

b. Operation and Support of TBM & DBM

For an excavation project as large as that proposed, a good portion of the available national machine excavation resources will be required. The requirements for specified schedules of excavation and the available resources must be evaluated in terms of the requirements for both (1) the conventional excavation, and (2) the egress excavation.

The operation and support of a large number of TBMs in one large project has no precedent in excavation history. It is apparent that several machine manufacturing companies and a large number of contractors will be involved, particularly if an early deadline is set for completion of the conventional excavation. Also, a coordinating or management firm will be required to supervise the whole project.

Items that must be considered are:

1. Number of openings to the surface for entrance of the machines, utilities, and muck removal
2. Number of headings and machines to be operated at one time
3. Lead time for construction of machines
4. National capabilities for machine construction
5. Source of power. This may determine 2 above.
6. Placement cutters and repair parts
7. Engineering and geological staffs
8. Muck disposal on the surface
9. Plan of surface transportation, i.e., road layout with respect to topography
10. Other

For a post-attack underground environment under the most severe conditions, all of the operational support for a given egress machine must be available at an isolated site underground. This includes operational

personnel who can run the equipment and perform maintenance and repairs, as well as personnel to maintain and launch the missile, plus necessary spare parts, tools, extra cutters, power, ventilation, means of muck disposal, and compressed air.

c. Collect TBM Data and Project Same for Fifty Year Period

Much of the data on TBM operations had already been compiled in various studies, which are described in Volume II and Appendix A, and have been extended to include pertinent available data for projects in the U.S. and abroad.

d. Near Term Improvements

Many of the recent improvements in tunneling machine technology and economics are described in the compilation from the literature survey (Volume II). Some costs of items have been on the decline, while inflation and labor costs will continue to increase. Reasonable projections have been made for the next fifty years.

One of the most encouraging techniques for possible improvement of penetration rates for both hard and soft rocks is the use of high pressure water jets. Water jets may be a factor in the overall increase in advance rates if it is found to be feasible to use them.

Two of the most critical factors which contribute to high costs are variability in the properties of rock and the occurrence of zones of very weak rock, both of which may contribute to costly delays. Developments in machine design to solve these types of problems have been partially solved by some of the TBM companies. Tunneling around curves is also a costly operation, and machine and tunnel design to alleviate this problem have been carried out.

e. Cost Projections

In general, detailed costs of tunnel excavation projects are not available. However, reasonably accurate cost studies were made with the cooperation of machine manufacturing companies, owners of tunnels, and consultants in tunnel construction.

General cost items include:

- Capital costs
- Labor
- Materials
- Supplies
- Energy
- Overhead
- Other

These were further broken down into subcategories and the effects of the factors utilized to determine projected costs utilizing a computer program (COSTUN). Most of the required cost items are reasonably predictable, as well as the effects of new near term technological developments and other cost factors.

f. Optimization of Advance Rates and Resources

The results of the linear cutting tests served as a base for predicting penetration rates in rock from the proposed DBM site. Details of geologic structure were assumed for accurate advance rate prediction for various types of geologic conditions to be encountered and were approximated for the excavation costs based upon assumptions of different percentages of good, medium, and bad ground.

Optimization of local resources for conventional tunneling is usually determined by the bid specifications. The optimization of national and even international resources will constitute a major problem in terms of manufacture of the required number of machines, acquisition of skilled labor, energy, etc.

Recommendations of the optimization of resources for post-attack excavation is also one of the objectives of this study. These are initial approximations only and must be finalized based upon experience in the conventional tunneling phase.

g. TBM Reliability

The reliability of conventional tunneling machines is fairly well established and is predicted for the proposed excavation based upon rock properties, geologic conditions, and recent downtime experience in rocks similar to expected sandstones.

Reliability under post-attack conditions can be maximized by studies of tunnel boring experience in the conventional tunneling, by depth of training of personnel, by diamond drilling of each egress site to the surface, and making similar provisions. For short distances, machine reliability should be relatively high.

TASK II

a. Multiple Use of TBM

Inasmuch as the same types of excavation conditions may be encountered in both conventional and egress tunnels, it would appear that modified machines might serve for post-attack usage, or that machines of simplified construction will be more reliable. The local egress site condition will probably be affected by an attack, and hence, the machines should be designed for bad ground conditions. This is also true to a lesser extent for the machines to be used in conventional tunneling because of the extensive nature of the project every machine used is likely to be required to excavate in good and bad ground.

b. Optimum TBM Operational Environment.

Due to the extensive nature of the excavation and the fact that the tunneling machines will encounter good and bad ground, optimization of equipment will be accomplished by its flexibility to operate under a range of rock conditions, including those types of sandstones which will stand alone for a short time to those which require immediate support in fault zones.

Where possible, the permanent openings and the egress openings should be located in stable, readily boreable rock. This can be accomplished by a layout based upon reliable geological information. The ground between the ETBMs and the surface should be explored with diamond drills so that pre-attack egress tunneling conditions are known, and a means should be provided for determining post-attack conditions.

TASK III

a. Modified TBM

The ETBMs will incorporate essential features of the most recent design which show the most flexibility and reliability in the excavation of weak rock in the DBM complex. Several machine manufacturing companies have modified machine designs so that relatively unstable ground can be machine excavated. In addition to TBMs, other types of equipment suitable for excavating the egress openings may be considered (see Novel Ideas).

b. Potential Egress

The primary problems for egress machines stem from:

1. Power needs.
2. Ventilation.
3. Muck disposal.
4. Reliability.

5. Simplicity of operation and maintenance

6. Operation in fractured weak rock

These factors were considered with respect to the DBM post attack environment out to, but not including, the rubble zone.

c. Design Trade-Offs

There are some possible areas for design trade-offs for the ETBM, such as the muck disposal system, and the possible use of high pressure water jets to increase the rate of penetration. The expected short period of operation may permit the use of a less rugged, lighter machine.

d. TBM Specification

Problems involved in simplification are concerned primarily with machine operation and the interface between the machine and the rock. Machine breakdown can be minimized with respect to motors, gears, etc. Cutter wear is usually a major problem, as is cutter bearing failure. Beyond these items, the judgment involved in how to solve problems which arise because of the nature of the rock or rock structure is critical. There is no substitute for experience, and the machines cannot be made foolproof. They must also be capable of operating in relatively stable and weak rock.

Hence, one approach to this problem will be to provide a maximum of training for key personnel, possibly in the excavation of the main tunnel complex and to make the ETBMs as simple and foolproof as possible.

TASK IV

a. Sample Procurement

Representative samples of rock approximately 3 x 3 x 1-1/2 feet were obtained for testing in the large linear cutter.

Eight pieces of this size of sample as well as smaller samples were obtained from typical geologic formations which might be considered for DBM siting.

b. Rock Tests and Prediction

Laboratory cutting tests were performed on rock samples to be obtained from the excavation site using the large linear cutting machine. Tests were undertaken at various levels of spacing and penetration to determine cutter load behavior and relationships of the parameters involved.

Rock cores were also tested to determine basic rock mechanical properties. Previously developed predictor equations were employed in conjunction with rock compressive and shear strengths to predict cutter forces and performance.

c. Identify Best ETBMs

From the operational factors and the laboratory experimentation, rates and costs were predicted. This information, together with logistic factors, was employed for recommendation for the design of the best ETBM by two companies, Jarva and Robbins.

d. Application of Water Jets to ETBMs

High pressure jets have been shown to be effective in hard rocks such as granite. Laboratory tests have shown that significant increases in penetration rates are possible by using low pressure jets positioned to travel in the cutter path. Reduced water pressure increases the system reliability as the pumping equipment for generating such low pressures (about 5,000 psi) is commercially available and has proven quite reliable for long periods of operation.

Laboratory tests on the rock to be bored for the proposed excavation were made to determine its water jet cutting characteristics. It is pro-

posed that water jets be considered for possible use as an assist to reduce energy requirements. However, except in weak ground, it is expected that a TBM may excavate the rock faster than it can be mucked and hauled to the portal. This final information was then employed for application of the laboratory results to prediction calculations.

e. Cost Estimates

Cost estimates (total and cost per meter of tunnel) were made for TBMs by three different methods. Procedures are well established for different general rock types by consultants and boring machine companies. These results are compared and discussed showing the probable range of estimated cost values. A sophisticated computer program was used for cost calculation, assuming that the tunnels will require concrete lining.

Novel Ideas

There are alternative, but unproven, methods which might prove more effective than the mechanical boring machines for the excavation of post attack egress openings.

For the egress mission in which the primary objective is to excavate as rapidly as possible, boom type cutters, especially the newer models with twin booms, may prove advantageous. Depending on the abrasiveness of rock, cutter costs could be high, but this does not appear to be a major consideration for excavation egress tunnels. Boom type cutting machines have high mobility compared to TBMs, which can provide flexibility for the excavation and probably permit drivage of several adjacent egress tunnels with the same machine. If the rock proves to be too hard for the boom cutters to excavate, water jets may be added to the system. Since pumps to generate the required low pressures are commercially available and are

built of proven components, incorporating water jets to assist the boom cutter should not cause a reduction in the system reliability.

Large hole drilling machines can also be used for excavating the egress tunnels. At present, machines that can drill holes up to 7 ft in diameter and over 300 ft in length with or without a pilot hole are available and are being used in various underground construction jobs with reasonable success. The major advantages of these machines are the low cost and simplicity compared to TBMs. The machines are relatively easy to operate and have high mobility. They are powered with diesel engines which further add to mobility.

Materials Handling - Egress

Due to the conditions under which the egress mission is to be carried out, material handling can be as critical as the excavation process. One idea is to drill a small hole ahead of the machine to the surface and use a screw conveyor to transport the cuttings. This system, however, may require some type of surface facility to dispose of cuttings, a requirement which might preclude its application.

Another possible means of muck disposal is to convey the cuttings from the tunnel face to an existing underground dump site. This would require that a large opening be created close to the egress tunnel prior to excavation which has a capacity to handle the muck from one or several adjacent egress tunnels. Since the diameter and length of egress tunnels will be known in advance of egress tunnel excavation, a room of sufficient size to accept the required amount of muck can be excavated.

One or more transport systems can be used for muck removal from the tunnel face. A requirement of the muck transport system is that it should be continuous in order to permit a continuous excavation to realize fast

egress. Pneumatic or hydraulic transports could fulfill the requirements, although hydraulic transport may not be desirable due to requirements of water storage and slurry treatment for disposal. Use of flexible conveyor belts is another possibility particularly for the short lengths of egress tunnels to be bored. Trackless haulage equipment (shuttle cars) can be used, but such equipment may require intermittent excavation.

Support

With regard to the tunnel support in broken rock, a shield-type lining that can be attached to the boring machine and actuated hydraulically appears most promising. This shield can be made to cover part of or the entire tunnel circumference and can be built in segments of appropriate lengths to negotiate curves. Use of a full circular shield would be limited to very bad, loose ground. If rock appears intact and competent, then temporary roof support requirements can be met with roof bolts, either mechanical or resin grouted and shotcrete, which may be sprayed from a nozzle mounted on the machine. Regardless of which support system is used, roof support should be easy to install and to provide at least temporary support for the missile launcher to pass through.

CHAPTER 2

ROCK PROPERTIES AND PENETRATION RATES

Sample Collection

The rock samples required for laboratory testing were collected by CSM's personnel from a site identified by the Air Force. The site is located between mileages 56 and 58 on Route 65, which is approximately 20 miles northeast of Grand Junction, Colorado. Route 65 runs along the Plateau Creek Valley between the Grand and Battlement Mesas as shown in Figure 1. The rock formations in this area are mainly composed of buff-colored sandstones with interlying shale, clay, and limestone beds. The stratigraphy of the Grand and Battlement Mesas areas is described in Table 3.

Prior to sample collection, the field site was visited several times in order to locate suitable rock boulders and to make the necessary arrangements for the quarrying operation. Concurrently, the Bureau of Land Management (BLM) office in Grand Junction was contacted to obtain permission to quarry and remove the selected rock samples from the designated area. The permission was granted after the area was checked by BLM personnel for presence of any landmarks of archaeological value.

In field selection of rock samples, two factors were given prime consideration. First, the rock samples to be quarried and removed had to be in an accessible location and away from the highway so as not to interfere with traffic. Second, the rock samples had to be intact, free of major fractures or joints, and not show any weathering effects. In field trips to the designated area, several large boulders, which closely met these requirements, were located lying beside the highway. These boulders were, however, rather large and had to be split into smaller pieces to bring

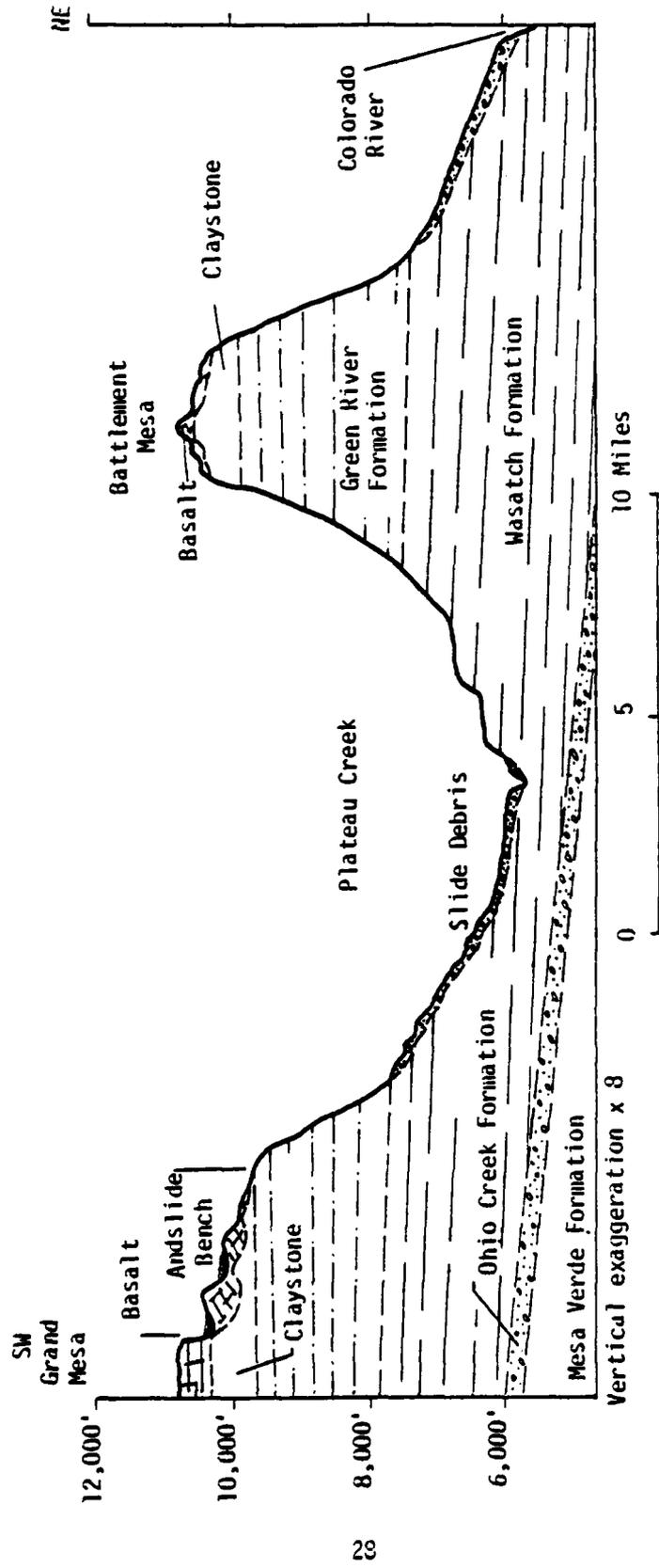


FIGURE 1 - Diagrammatic Cross Section from Grand Mesa through Battlement Mesa to the Colorado River

TABLE 3
PRE-QUARTERLY STRATIGRAPHY OF THE
GRAND AND BATTLEMENT MESAS AREA*

System	Series	Formation	Member	Thickness (feet)	Rock description	
Tertiary	Pliocene	Intrusive and extrusive rocks Unconformity		200-500	Basalt flows, dikes, and sills 9.7 ± 0.485 million years potassium argon).	
	Pliocene(?)	Unnamed sedimentary rocks Unconformity		50-900	Gravel and variegated claystones.	
	Eocene	Green River Formation	Evacuation Creek		500	Light-brown and gray sandstone and gray marlstone and siltstone; in places, contains pelecypods, gastropods, ostracodes, and vertebrate fragments.
			Parachute Creek		600	Predominantly black, brown, and gray oil shale that in places forms cliffs; contains minor amounts of gray siltstone and gray and brown fine- to medium-grained sandstone; contains richest oil-shale beds.
			Lower		1,000	Fine- to coarse-grained gray and brown sandstone, minor amounts of gray siltstone and marlstone, and a few thin tan low-grade oil-shale beds.
		Wasatch Formation	Upper		400-1,600	Variegated shale and clay and some lenticular beds of sandstone, conglomerate, and limestone.
			Middle		0-400	Massive fine- to coarse-grained gray and brown sandstone, in part conglomeratic; conspicuous ledge former. Pinches out on west flank of Chalk Mountain.
			Lower		400-900	Variegated shale and clay and some lenticular beds of sandstone, conglomerate, and limestone.
	Unnamed rocks			(?)	Brown and somber-colored shale with thin coal seams.	
	Paleocene	Ohio Creek Formation			10-150	Massive fine- to coarse-grained white to brown sandstone; in most places, contains pebbles and cobbles of quartz, quartzite, chert, and some limestone and granite pebbles.
Cretaceous	Upper Cretaceous	Mesaverde Formation		2,000-3,300	Fine- to medium-grained ledge-forming brown sandstone interbedded with gray shale, carbonaceous shale, and some thin coal beds.	

*Adapted from J.R. Donnell, unpublished data, 1956, organization unknown.

them back to the laboratory for testing. To accomplish this, each boulder was line drilled and split using hydraulic splitters. This process worked very satisfactorily as reasonably smooth rock surfaces were produced from the splitting operation. Following this, two trips were made to the field site with each trip bringing back about four rock pieces, each piece weighing approximately five tons. These rocks were further split into smaller pieces to sizes suitable for linear cutting tests. Each rock sample was cast in concrete and marked for identification according to location where it was acquired. Figure 2 shows a picture of the field quarrying operation. A picture of the canyon walls in the approximate vicinity of the sample collection site is shown in Figure 3.

To determine any variation in rock type, hand samples were taken from each rock piece and petrographic analysis performed. This analysis revealed that there were actually two distinct types of sandstone. As will be discussed later in this report, the presence of two types of sandstone were also reflected in analyzing the results of the physical property tests. For identification purposes, these two sandstone types were then referred to as "soft" and "hard" sandstones.

The results of the petrographic analysis are summarized in Tables 4 and 5 for soft and hard sandstones, respectively. The major difference between the two appears to be the grain size, as well as the deposition environment.

Cores were prepared from the samples of each rock type for physical property tests. ASTM standards were followed in core preparations. For each sandstone type, tests were performed to measure the compressive, tensile, and triaxial strength of rock. Each strength was determined by testing ten samples in order to gain a representative average value. Figure 4 shows some of the cores for the compressive and tensile (Brazilian) strength testing. The purpose of performing triaxial strength tests was to determine



FIGURE 2 - Field Quarrying of Sandstone Samples



FIGURE 3 - Canyon Walls Along the Plateau Creek Valley

TABLE 4
SOFT SANDSTONE

Petrographic Analysis

Color: Buff

Texture: Medium to coarse grained sand, moderately well sorted, argillaceous, high porosity and permeability

Mineralogical Composition:

Quartz sand	75%
Feldspathic sand	10%
Micaceous material	5%
Black grains - chert	5%
Calcareous cement	5%

Classification: Argillized, cherty, micaceous, calcareous feldspathic sandstone

Origin: Alluvium deposits

Physical Properties

Compressive strength:	3,900 psi
Tensile strength :	238 psi
Shear strength :	500 psi

TABLE 5
HARD SANDSTONE

Petrographic Analysis

Color: Buff

Texture: Fine medium grained sand with clay clasts, well sorted, argillized calcareous cementing, medium porosity and permeability

Mineralogical Composition:

Quartz sand	75%
Feldspathic sand	15%
Clay clasts	5%
Calcareous cement	5%

Classification: Argillized, feldspathic w/clay clasts, calcareous sandstone

Origin: Alluvium deposits farther from material source than the soft sandstone

Physical Properties

Compressive strength: 6,054 psi

Tensile strength : 339 psi

Shear strength : 790 psi



FIGURE 4 - Core Samples for Compressive and Tensile (Brazilian) Strength Testing

rock shear strength. Using the triaxial test data, Mohr's envelope was constructed for each sandstone type and the shear strength was estimated as the intercept of the envelope with the shear axis. These shear strength values are included in Tables 6 and 7 along with the measured compressive and tensile strengths.

As indicated, both types of sandstone have low strengths. Moreover, their densities are low, indicating reasonably high porosities.

In parallel with the physical property determinations, linear cutting tests were performed (Figures 5 & 6). These tests were undertaken using a large linear cutting machine capable of simulating field cutter loads and penetrations. This machine can also accept any size commercial cutter and has been shown to simulate field boring conditions very closely. Past studies in correlating the cutting results obtained from this machine with actual field data has been very successful. A full description and operating procedures of this machine are given elsewhere.

A disc cutter of 12-in. diameter and 75° edge angle was chosen for linear cutting tests. There was nothing unique about this choice except this particular cutter appeared to meet the requirements most favorably. Its size and edge angle were believed to be appropriate for boring a 15-ft diameter tunnel in sandstone, as envisioned.

A total of three linear cutting tests was performed in samples of each sandstone type. The cut spacing was held constant at 3 inches, and the cutter penetrations of 0.20, 0.30, and 0.40 inches were tested. Each test consisted of a minimum of four passes over the rock surface with each pass containing an average of five cuts. Due to softness of the sandstone tested, some samples were found to split during testing. This resulted in anomalous behavior of cutter forces which required the repetition of some

TABLE 6
THE RESULTS OF PHYSICAL PROPERTY TESTS FOR SOFT SANDSTONE

A. Compressive Strength Tests

Test No.	Diameter (in.)	Length (in.)	Weight (g)	Density (g/cm ³)	Failure Load (lbs)	Strength (psi)
1	2.135	4.071	497.9	2.09	8,900	2,486
2	2.137	3.947	482.1	2.08	11,000	3,066
3	2.129	4.005	485.0	2.08	17,600	4,943
4	2.136	4.001	487.4	2.08	13,700	3,848
5	2.134	4.021	489.7	2.08	19,200	5,368
6	2.132	4.040	497.8	2.11	15,400	4,313
7	2.137	3.917	478.2	2.08	11,500	3,206
8	2.130	4.026	488.4	2.08	12,750	3,578
9	2.133	4.073	502.4	2.11	15,750	4,407
10	2.129	4.138	496.7	2.06	13,600	3,820
						Avg. = 3,900 psi

B. Tensile (Brazilian) Strength Tests

1	2.133	1.130	133.1	2.01	850	224
2	2.126	1.109	132.7	2.06	1,100	297
3	2.134	1.074	128.2	2.04	750	208
4	2.129	1.166	139.4	2.05	1,100	282
5	2.141	1.135	131.1	1.96	600	157
6	2.144	1.170	139.1	2.01	1,150	291
7	2.132	1.162	139.4	2.05	1,200	308
8	2.133	1.176	139.7	2.03	750	190
9	2.133	1.191	142.1	2.04	1,000	250
10	2.128	1.127	133.0	2.02	650	172
						Avg. = 238 psi

TABLE 6 (Cont'd.)

C. Triaxial Strength Tests

Test No.	Diameter (in.)	Length (in.)	Weight (g)	Density (g/cm ³)	Confining Pres. (psi)	Failure Loads (lbs)	Strength (psi)
1	2.133	3.939	485.6	2.11	250	33,000	9,235
2	2.131	4.013	492.0	2.10	500	36,000	10,093
3	2.140	4.017	487.1	2.06	750	43,500	12,094
4	2.135	4.094	499.3	2.08	1,000	41,500	11,592
5	2.138	3.968	486.1	2.08	1,250	39,000	10,893
6	2.139	4.027	493.0	2.08	1,500	44,000	12,244
7	2.139	4.048	483.9	2.03	1,750	51,000	14,192
8	2.135	4.044	486.7	2.05	2,000	51,000	14,245
9	2.134	3.983	492.9	2.11	2,250	57,500	16,076
10	2.132	4.096	494.7	2.07	2,500	57,500	16,106

Triaxial Shear Strength (determined from Mohr's envelope) = 500 psi

TABLE 7

THE RESULTS OF PHYSICAL PROPERTY TESTS FOR HARD SANDSTONE

Test No.	Diameter (in.)	Length (in.)	Weight (g)	Density (g/cm ³)	Failure Load (lbs)	Strength (psi)
A. Compressive Strength Tests						
1	2.131	4.142	513.8	2.12	17,200	4,822
2	2.130	4.037	502.6	2.13	18,500	5,191
3	2.128	4.142	523.5	2.17	22,800	6,410
4	2.123	4.199	521.2	2.14	17,700	5,000
5	2.135	4.002	539.6	2.30	33,500	9,357
6	2.132	3.967	498.2	2.14	20,750	5,812
7	2.144	3.965	406.9	2.16	19,900	5,512
8	2.134	3.984	506.7	2.16	21,500	6,011
9	2.130	3.975	500.8	2.15	22,700	6,370
10	2.130	3.972	498.2	2.14	21,600	6,061
						Avg = 6,054
B. Tensile (Brazilian) Strength Tests						
1	2.140	.988	122.6	2.10	1,150	346
2	2.134	1.016	126.9	2.13	1,500	440
3	2.140	1.034	128.3	2.10	1,450	417
4	2.136	1.012	124.7	2.09	1,600	471
5	2.138	1.000	126.2	2.14	750	223
6	2.132	.996	124.2	2.13	700	209
7	2.135	1.011	126.0	2.12	750	221
8	2.134	1.007	125.7	2.12	1,250	370
9	2.133	1.002	124.6	2.12	1,200	357
10	2.133	1.044	132.6	2.16	1,200	343
						Avg = 339

TABLE 7 (Cont'd.)

C. Triaxial Strength Tests

Test No.	Diameter (in.)	Length (in.)	Weight (g)	Density (g/cm ³)	Confining Pres. (psi)	Failure Load (lbs)	Strength (psi)
1	2.135	4.016	511.3	2.17	250	37,000	10,335
2	2.130	3.982	504.9	2.17	500	40,000	11,225
3	2.130	3.965	495.04	2.13	750	39,000	10,945
4	2.130	3.986	499.6	2.14	1,000	42,000	11,787
5	2.130	3.964	501.2	2.16	1,250	51,500	14,453
6	2.130	3.960	503.5	2.17	1,500	53,500	15,014
7	2.135	3.930	496.6	2.15	1,750	54,000	15,084
8	2.130	3.952	492.9	2.13	2,000	60,000	16,838
9	2.139	3.70	498.3	2.13	2,250	65,000	18,088
10	2.130	3.940	496.75	2.15	2,500	62,000	17,400

Triaxial Shear Strength (determined from Mohr's envelope) = 790 psi

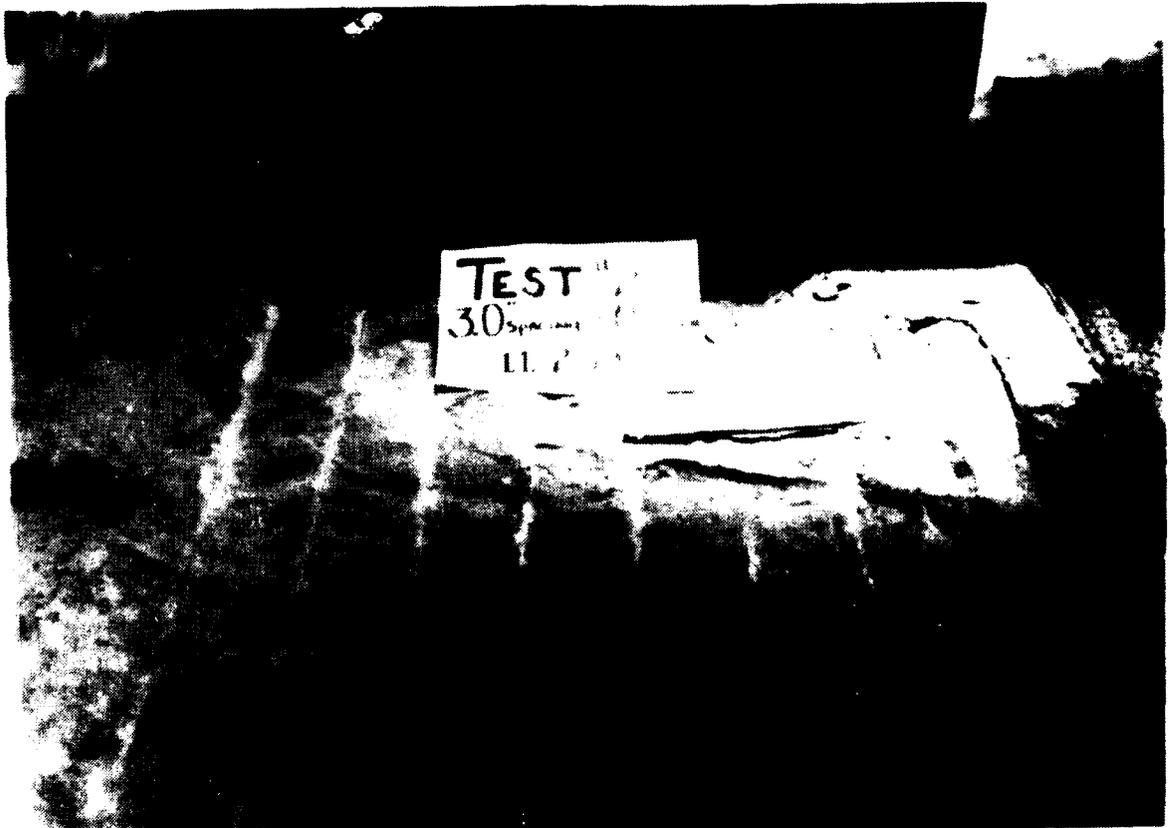


FIGURE 5 - Linear Cutting Tests in Sandstone

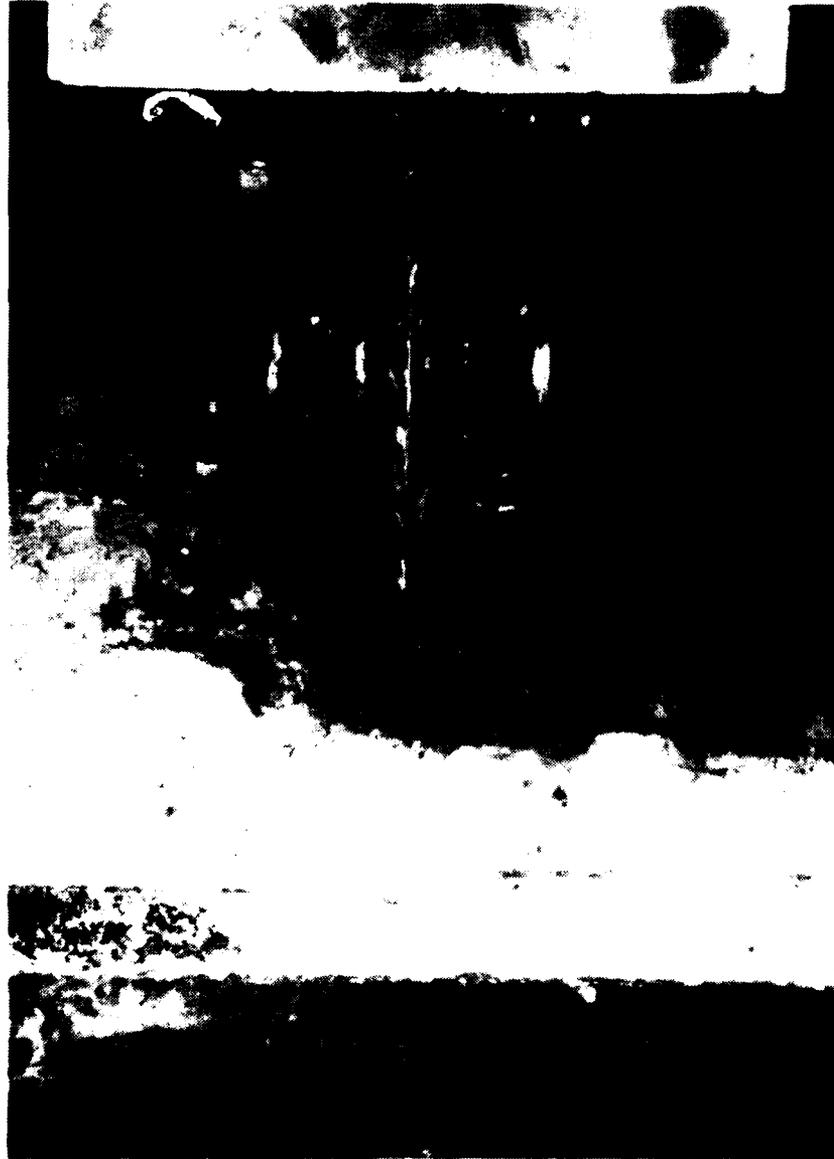


FIGURE 6 - Cutting of Sandstone with a 12" - 75° Disc Cutter

tests in new, fresh rock samples. The test results are summarized in Table 8. As seen from the results, the cutting forces in both types of sandstone, even at a penetration of 0.40 inch, are far below the allowable bearing capacity of 12-in. diameter disc cutter which has a design load capacity of about 30,000 lbs. This means higher penetrations than those tested here can easily be achieved without overloading the cutter bearings. Several visual observations were made during testing. First, extensive dust was generated during the cutting process. Second, especially for soft sandstone cutting, the rock chips were found to crumble very easily. The field implication of this finding is that the large chips dislodged from the tunnel face by the cutters may disintegrate into much smaller pieces as they fall onto tunnel invert and are picked up by muck buckets. As regards the extensive airborne dust, the machine will be required to have sufficient dust suppression and removal capacity in order to keep a reasonably dust-free heading.

The purpose of carrying out linear cutting tests was to determine the boreability of this rock formation. Though this subject will be discussed in more detail later in this report, the linear cutting results show that high penetration rates can be attained in boring both sandstone types. That is, from a penetration rate standpoint, this particular sandstone formation possesses favorable characteristics for efficient machine boring. As indicated by the results, even at an individual cutter load of one-third of its bearing capacity, the machine can achieve a 0.40 inch penetration per cutterhead revolution. Assuming a cutterhead speed of 10 rpm for a 15 ft diameter machine, this translates into a penetration rate of 20 ft/hr. This value is, of course, the instantaneous penetration rate, and therefore, to determine the average advance rate, the machine utilization should also be taken into account. It is obvious that this penetration rate can be substantially increased by increasing the machine thrust so as to exert higher

TABLE 8
THE RESULTS OF LARGE LINEAR CUTTING TESTS USING A 12-in. - 75° DISC CUTTER

Test No.	Penetration (in.)	Spacing (in.)	No. of Cuts	Average Side Force (lbs)	Average Vertical Force (lbs)	Average Rolling Force (lbs)
A. Soft Sandstone						
1	.20	3.0	21	902	4,020	486
2*	.30	3.0	23	1,062	5,423	732
3*	.40	3.0	19	1,860	8,974	864
B. Hard Sandstone						
1	.20	3.0	22	951	6,035	602
2	.30	3.0	20	1,442	7,278	968
3	.40	3.0	21	2,684	11,110	1,704

*These tests were repeated.

loads on each cutter without exceeding the allowable bearing capacity. This finding leads to the conclusion that the support requirements and other tunneling functions, such as muck haulage, may control the boring progress rather than the machine's ability to bore.

A major requirement set forth for the egress TBM is that it should be light weight, have high mobility, and incorporate flexibility of operation. Most tunneling machines are heavy pieces of equipment, and therefore, their mobility is rather limited. To reduce machine weight and as a result to increase its mobility, means must be found to somehow reduce the cutter force requirements to achieve a desired penetration rate. The machine performance can be improved through design changes, but the degree of improvement that can be gained is limited unless a major breakthrough toward better design is realized. There exists, however, another means of accomplishing this purpose which is to incorporate an auxiliary system on the machine to assist the cutters in their rock fragmentation effort. Water jets are one such system with proven background to serve this purpose.

The prime objective of introducing water jets into the cutting system is to reduce cutter load requirements for achieving a given penetration rate of the machine. If the cutter force requirements are lower, this will mean the machine can be built of a lighter frame since its power requirements are reduced. Consequently, its mobility is enhanced, the overall system can be of simple design, and cost savings are, therefore, realized.

Sandstone presents a very favorable medium for effective jet cutting. Its granular texture combined with high porosity permits the water jets to penetrate it very effectively.

Before water jets were applied to assist disc cutting action, preliminary jet kerfing tests were undertaken to delineate the jet cutting characteristics of sandstone. A block of soft sandstone was prepared and

slots cut with water jets. A total of four jet parameters, the cutting speed, standoff distance, jet pressure, and orifice size was studied and the resulting kerf depths measured. The results showing the effect of each jet parameter on the kerf depth are plotted in Figures 7 through 10. The trends depicted in these figures are as expected. Of major importance is that, due to high porosity, even low pressure water jets can cut this rock very effectively. Although not performed, similar results are also expected for hard sandstone.

Following these kerfing tests, water jets were introduced into the disc cutting system. The jet, utilizing a 0.025-in. orifice, was positioned ahead of the cutter so as to create a slot along the cutter path (Figure 11). The standoff distance was 4 inches, which appeared to provide sufficient protection of the nozzle from possible damage during the cutting process. The jet pressure was maintained around 5,000 psi, and this pressure was generated with a piston-type pump available in the laboratory. The reason for using low pressure was to provide good system reliability if a decision is made to install water jets on the DMB tunneling machine.

The comparison of jet assisted and pure mechanical cutting is given in Table 9. As can be seen, with jet assist, the cutter forces, especially the rolling force, is reduced by a significant amount. The field implication of this result is that the machine thrust and torque requirements can be reduced by incorporating water jets to assist the mechanical cutting action.

After the linear cutting tests with disc cutter were completed, it became apparent that because of their low strength, both sandstones could also be cut with drag bits. CSM has conducted extensive studies in cutting coal measure rocks with drag-type bits, both with and without jet assist. These tests have demonstrated that drag bit forces are significantly

Test Parameters:

Standoff distance = 4 in.

Jet pressure = 5,000 psi

Orifice size = .025 in.

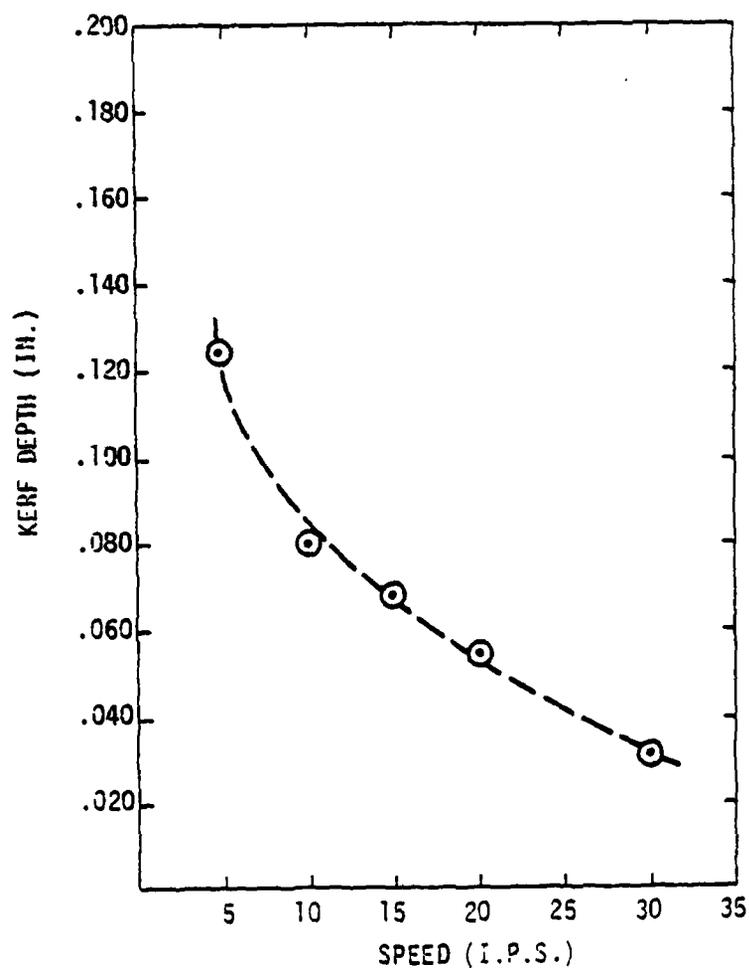


FIGURE 7 - Effect of Water Jet Cutting Speed on Kerf Depth in Soft Sandstone

Test Parameters:

Jet pressure: 5,000 psi

Orifice size: .025 in.

Cutting speed: 5 in/sec

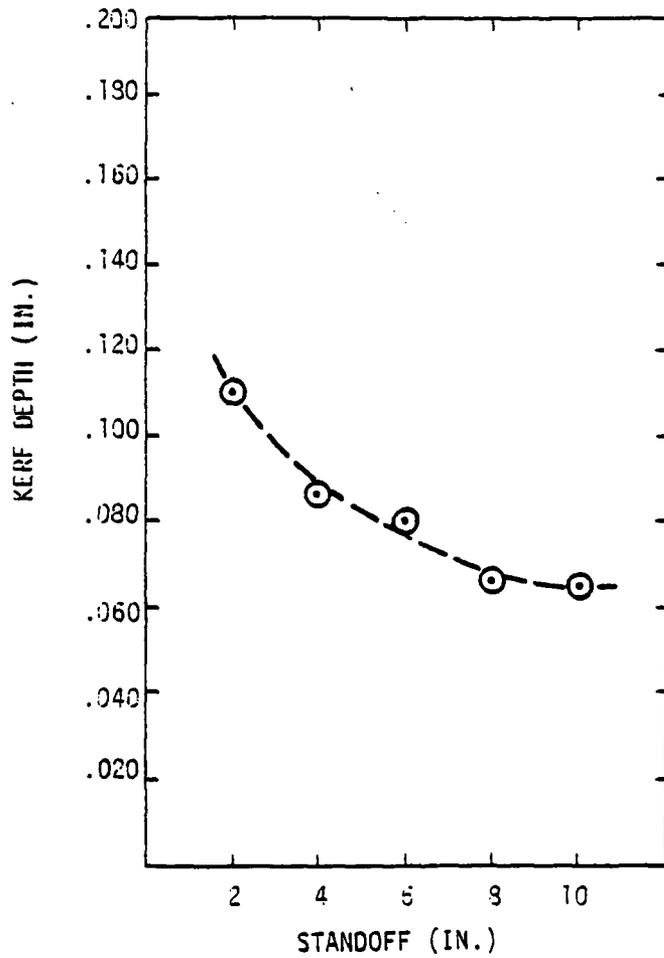


FIGURE 8 - Effect of Water Jet Standoff Distance on Kerf Depth in Soft Sandstone

Test Parameters:

Orifice size : .025 in.

Cutting speed : 5 in/sec

Standoff distance: 4 in.

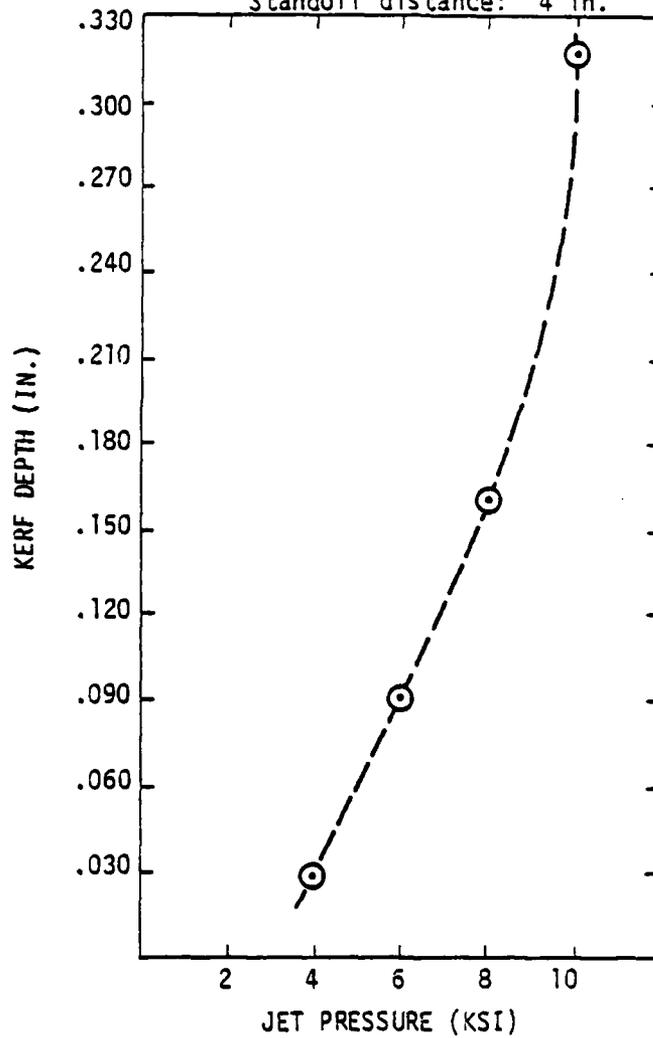


FIGURE 9 - Effect of Water Jet Pressure on Kerf Depth in Soft Sandstone

Test Parameters:

Cutting speed : 5 in/sec

Standoff distance : 4 in.

Jet pressure : 5,000 psi

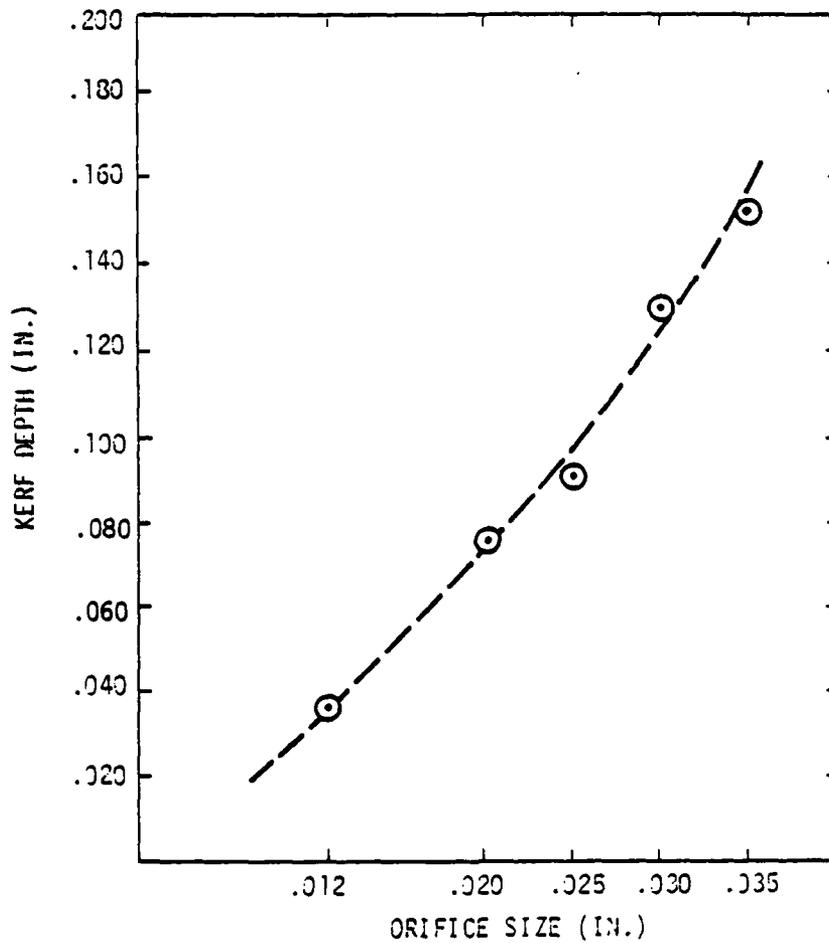


FIGURE 10 - Effect of Water Jet Orifice Size on Kerf Depth in Soft Sandstone



FIGURE 11 - Water Jet Assisted Disc Cutting of Sandstone

TABLE 9

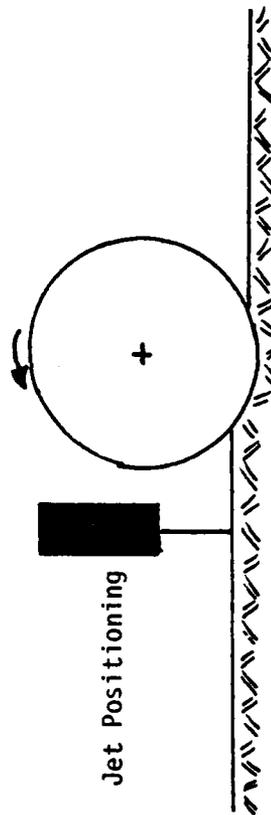
RESULTS OF DISC CUTTING TESTS IN SOFT SANDSTONE
(12-in. - 75° disc) ($C_0 = 3,900$ psi)

A. No Jet Assist

Spacing (in.)	Penetration (in.)	Vertical Force (lbs)	Rolling Force (lbs)
3.0	0.40	8,974	864

B. With Jet Assist (5,000 psi jet, 0.025-in. nozzle, 4-in. standoff distance)

Spacing (in.)	Penetration (in.)	Vertical Force (lbs)	Rolling Force (lbs)
3.0	0.40	6,845	389



reduced by jet assist. To apply the developed technique to present rock types, it was decided to conduct linear cutting tests using a conical (point attack) type bit. In these tests, the jet was positioned behind the bit and oriented to impinge the rock surface in the vicinity of the rock-bit contact point (Figures 12, 13, & 14). The jet pressure was again 5,000 psi using a 0.025-in. orifice size. Table 10 lists the test results. Substantial force reductions are seen to occur by introducing water jet to the immediate vicinity of the rock-bit contact point. Equally important was the dust suppression effect of water jet as generation of airborne dust was nearly eliminated when water jet was introduced to the cutting system.

Another important observation can be made from the drag bit test results. Note that even with no jet assist, the drag bit forces required to achieve a 0.40-inch penetration are considerably lower than disc cutting forces for the same penetration. However, the spacing used for drag bit cutting was half that of disc spacing. Hence, to allow a true comparison of the two cutting results, the drag bit forces need to be multiplied by 2 since twice as many drag bits as disc cutters will be required to bore a given size tunnel. Even if drag bit forces are increased by a factor of 2, the resultant values are still lower than those required for disc cutting. The major significance of this finding is that the TBM for excavating this sandstone can be equipped with drag bits instead of disc roller cutters, with much reduced power and thrust requirements, resulting in a lighter machine.

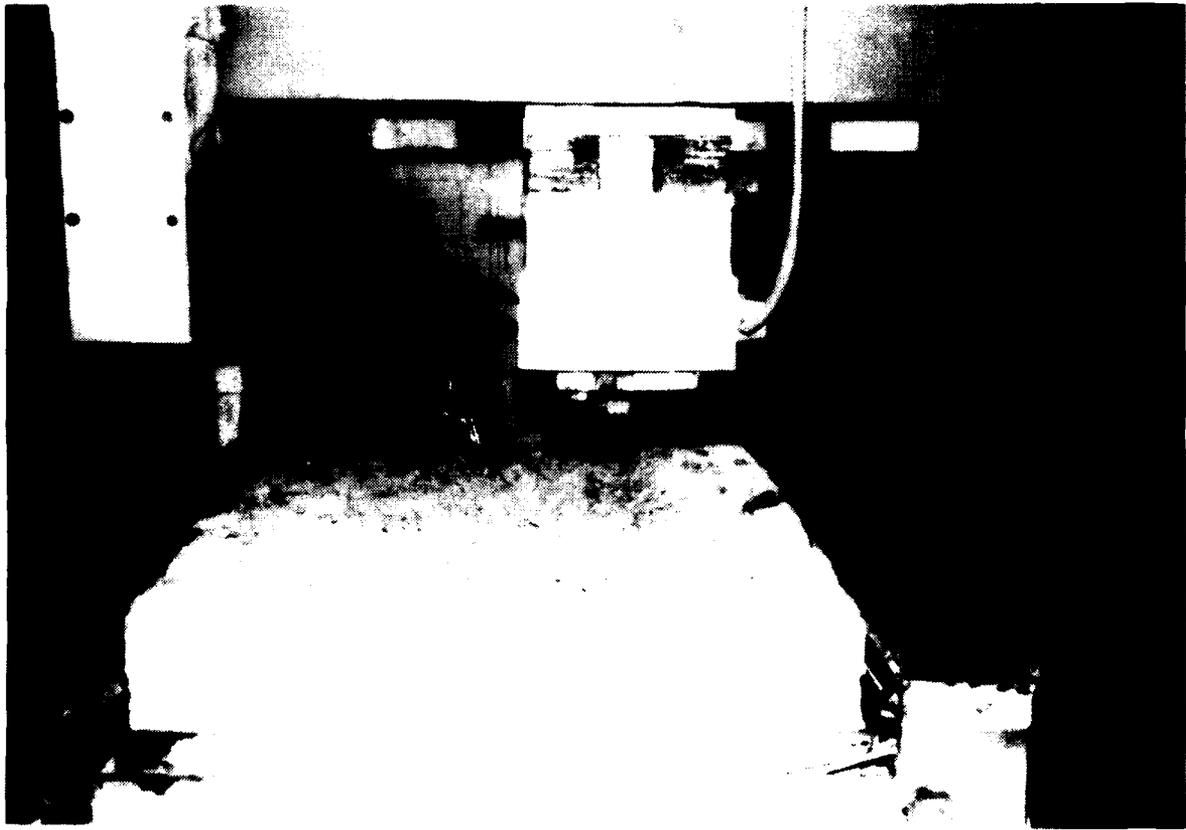


FIGURE 12 - Cutting Sandstone with a Conical (Point Attack) Bit

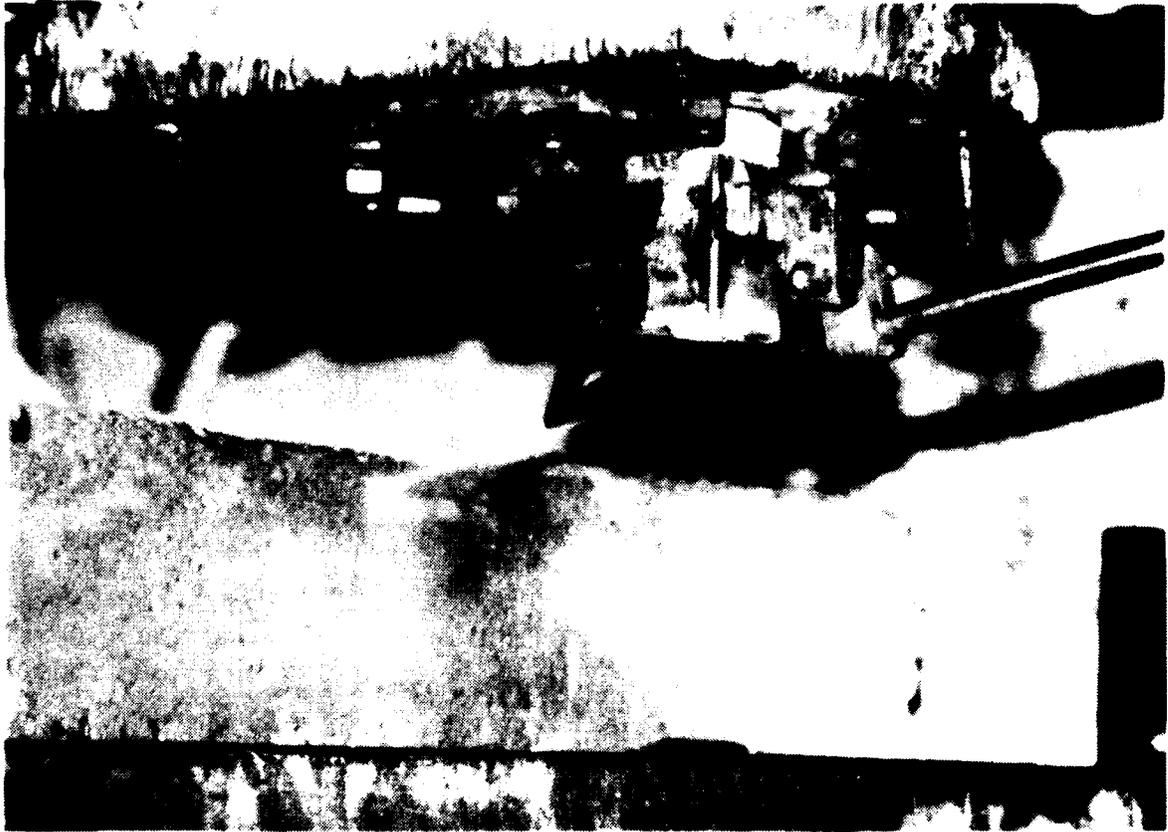


FIGURE 13 - Water Jet Assisted Drag Bit Cutting of Sandstone

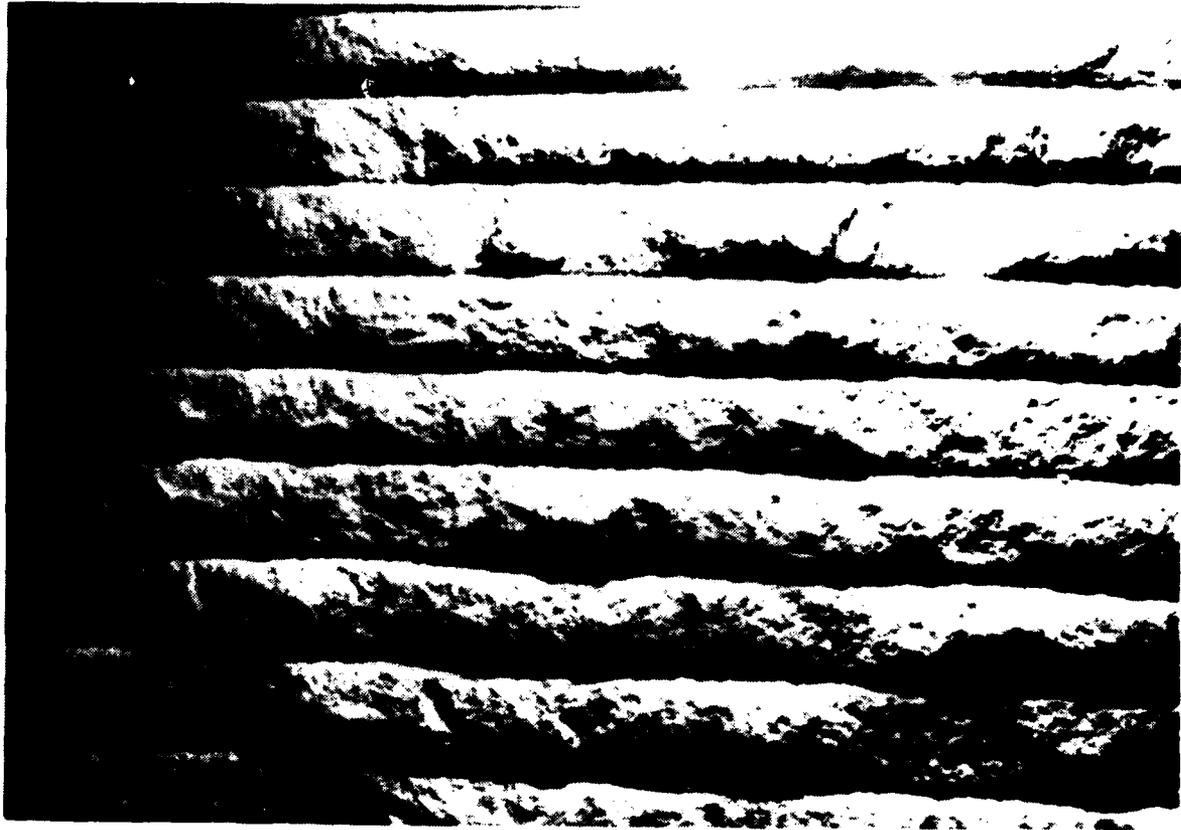
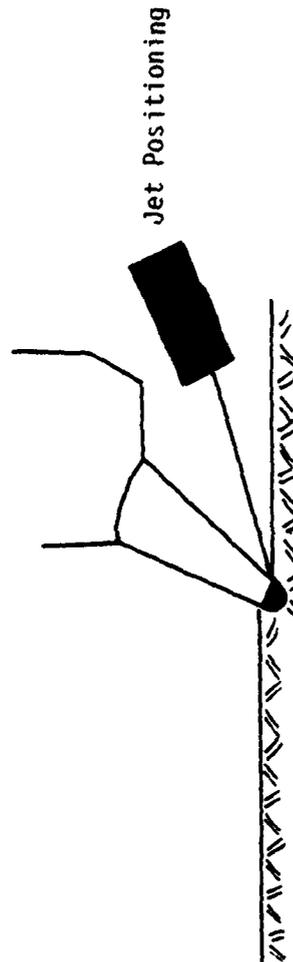


FIGURE 14 - Rock Surface Created by Water Jet Assisted Drag Bit
Cutting of Sandstone

TABLE 10
 RESULTS OF DRAG BIT CUTTING TESTS IN SOFT SANDSTONE
 ($C_0 = 3,900$ psi)

A. No Jet Assist						
Spacing (in.)	Penetration (in.)	Side Force (lbs)	Vertical Force (lbs)	Drag Force (lbs)	Side Force (lbs)	Vertical Force (lbs)
1.5	0.40	135	182	349		
B. With Jet Assist (5,000 psi jet, 0.025-in. nozzle, 4-in. standoff distance)						
Spacing (in.)	Penetration (in.)	Side Force (lbs)	Vertical Force (lbs)	Drag Force (lbs)	Side Force (lbs)	Vertical Force (lbs)
1.5	0.40	118	54	215		



Prediction of Field Boring Rates

One of the major objectives of this study was to predict the field penetration rates to be attained by the tunnel boring machines. To serve this purpose, laboratory linear cutting tests were carried out and, as described in the preceding section, both sandstone formations possess favorable characteristics for effective machine boring as far as the penetration rate is concerned (Figures 15 & 16).

Another means of estimating field boring performance is to utilize predictor equations. These equations have been verified with extensive field boring data, giving accurate estimates of penetration rates provided that the rock is not highly jointed or fractured. In such cases, the predictions are always lower than those attainable since the equations do not account for joint effects on boreability (see Volume II).

Using the predictor equations, calculations were performed to provide estimates of boring rates in both sandstone formations. Figures 15 and 16 display the results in graphical form. It should be emphasized that the calculated penetration rate is the instantaneous value and, therefore, does not consider any machine utilization factor. The predicted penetration rates are based on using a total number of 30 cutters on the machine. This number of cutters for the given bore size corresponds to an average cutter spacing of 3 inches, which is typical of most present-day tunneling machines equipped with disc cutters.

The penetration rates depicted in these figures confirm the findings of linear cutting tests, in that high boring rates are possible if these rock formations are excavated with TBMs. However, such predictions may never be realized in actual field boring since other important considerations such as mud removal, lining requirements, and machine utilization

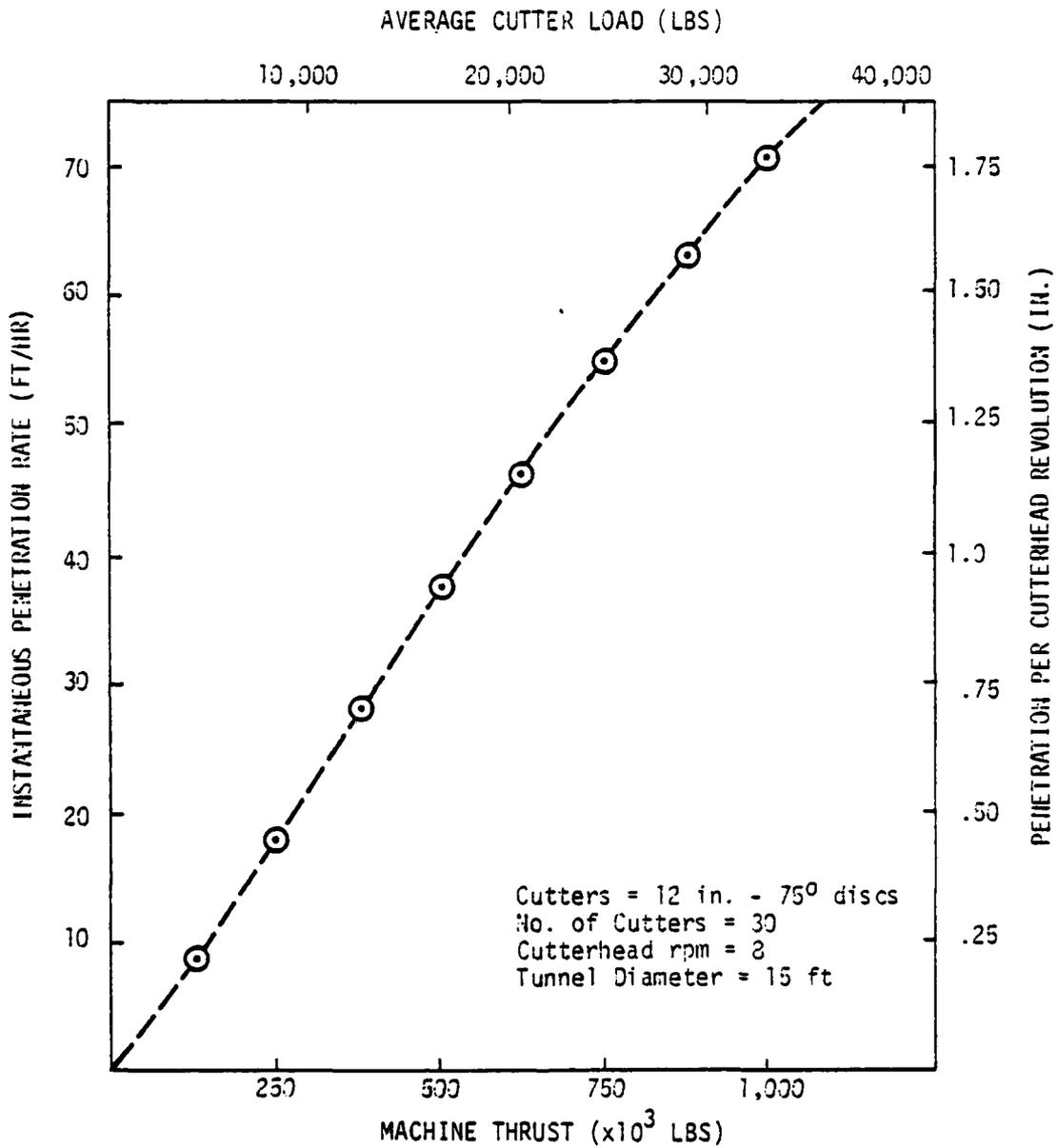


FIGURE 15 - Predicted Instantaneous Penetration Rate as a Function of Machine Thrust for Boring in Soft Sandstone ($C_0 = 3,900$ psi, $S_0 = 500$ psi)

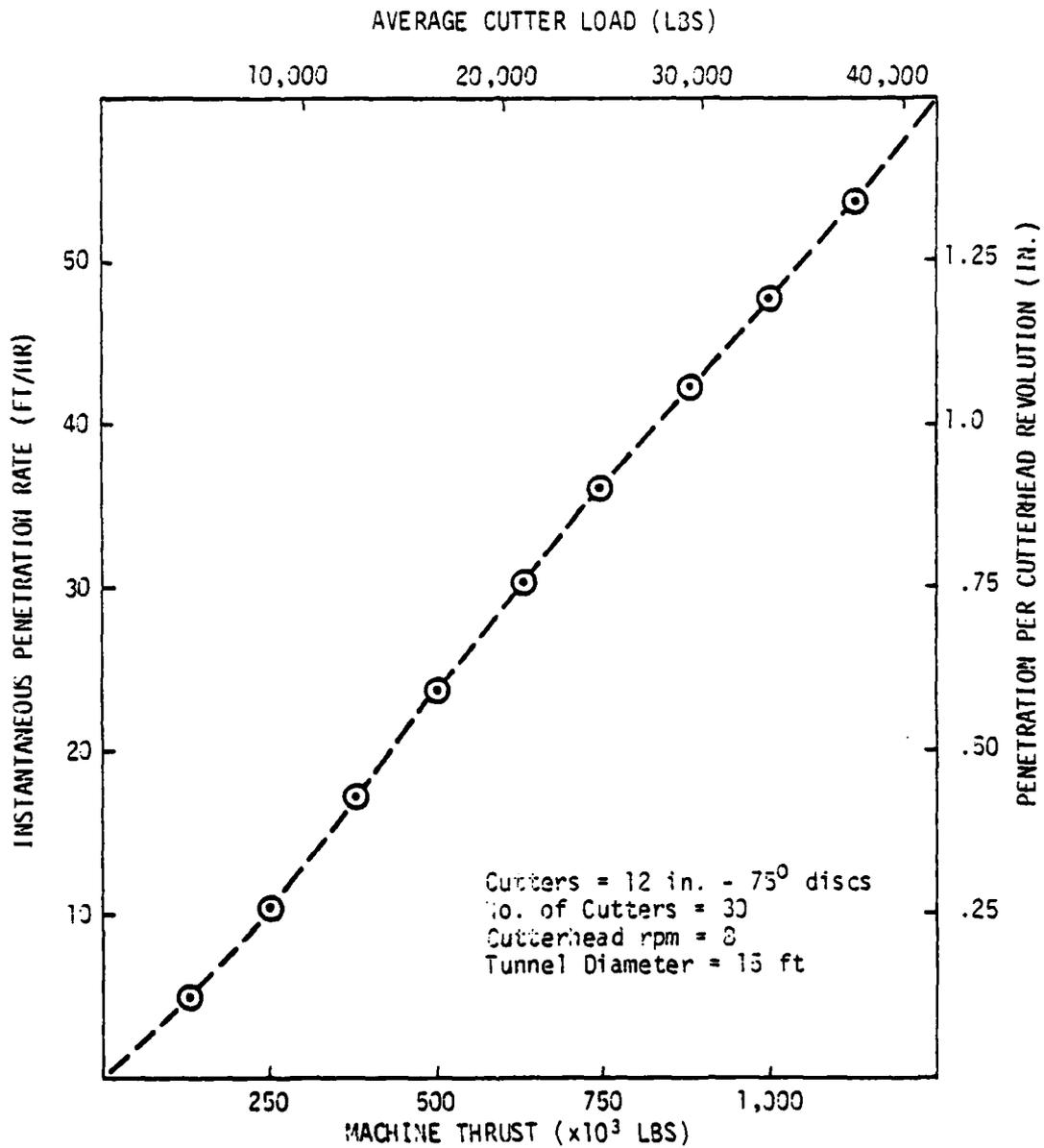


FIGURE 16 - Predicted Instantaneous Penetration Rate as a Function of Machine Thrust for Hard Sandstone ($C_0 = 6,050$ psi, $S_0 = 790$ psi)

can ultimately govern the efficiency of the whole boring operation, reducing the overall penetration rate to a value much lower than that predicted here.

CHAPTER 3
TBM - EGRESS (ROBBINS)
DESCRIPTION

General

The deep basing proposal calls for excavating an exit opening so an intercontinental range ballistic missile can be fired from deep underground. The TBM missile nest must be at least 2400 feet underground, and the exit tunnel should be completed within 10 days. The site must be in rock suitable to reduce the effects of surface attack and protect the installation.

Specifically, the problem of the tunneling system is to mine at a rate of 25 feet per hour for 20 hours of each day repeatedly for a maximum of 10 consecutive days. The material will probably be sandstone with an unconfined compressive strength of 6,000 psi. While being easy to mine, the weakness of the material probably means that full circumference lining should be placed behind the tunneling machine. However, this is dependent on specific site conditions.

The difficulties presented by this operation are no different than in any tunneling job, but the magnitude of several problems is affected by the advance rate and reliability requirements. The problems presented by hole-through (possible radioactive rubble) are quite unique.

a. Heading Advance

Experience in this type of material has shown that the advance rates demanded are not out of the question. A suitable demonstration project for the egress machine should lead to confirmation that the advance rates and reliability requirements can be met. High advance rates do require high horsepower. An estimate of the power required follows in the machine specifications, but again, these values will change as site conditions vary and will require more investigation.

b. Muck Haulage System

The average amount of muck to be removed at the required penetration rates for a 15-foot diameter hole approaches the amounts which currently are considered as records. Granting the short duration of the job, the removal and disposal of the muck presents a significant problem in terms of equipment reliability, haulage rate, and energy requirements. The approach illustrated in the following drawings solves this problem by eliminating the haulage system. This is accomplished by mining upwards at an angle of 30° or greater. The muck will then flow down the invert to the storage pit or tunnel. The invert liner section encloses the falling debris. While adding somewhat to the linear complexity, this approach eliminates the reliability problems, energy consumption, and cost of the haulage system. The dust problem will be reduced because no conveyor dump points exist and the broken material is completely separated from the working environment. The major advantage is that the missile can now be towed directly behind the TBM or brought up prior to hole-through without interfering with muck removal. The time between hole-through and firing of the missile should be reduced considerably. In addition, mining uphill has a positive effect on site availability as discussed below.

c. Lining Installation

Installation of the lining also presents a considerable problem because of the advance rate. The lining must be supplied in suitable quantities to the miners who must be able to assemble it at the rate required. The lining must provide adequate support while not being cumbersome. It should be possible to install by hand since introduction of unnecessary machinery is undesirable because of reliability factors. Design of the lining is a significant problem which should take into consideration site conditions, installation and handling, missile weight, and muck removal system.

d. Hole-Through and Missile Launch

The last stages of the exit construction involve holing-through and missile launch. It is assumed that the deep basing site will be attacked prior to initiation of the egress tunnel. Repeated blasting of the site exterior will lead to development of radioactive zones of rubble. These zones will be difficult to tunnel through because of the radioactive material which must be ingested by the site and because of unstable ground conditions. These zones must be audited. The exit path must be variable and controllable to avoid these areas and site selection must be such to eliminate the possibility of these zones occurring. Some way of investigating the material ahead must be utilized and sites selected must have the proper exterior geometry. This means that a considerable amount of vertical face must exist so that debris created by blast can fall away. It must be of sufficient height to accommodate the volume created. If horizontal boring only is considered, the overall site height would be increased over that required by a site suitable for mining uphill which also gives the required protective cover. Uphill boring therefore should increase the number of possible sites by lowering the requirements.

Possible rubble zones also will require full tunnel lining as close behind the cutterhead as possible.

Missile launch will require that the machine be removed from the tunnel or be an open cylinder to allow passage to the missile.

If the exit point is on a high bank, it should be possible to eject the entire machine to clear the tunnel for missile launch. This approach has the disadvantage that it must be a high bank with reasonably stable ground around the opening for it to be possible to eject the machine. The hollow machine has the advantage of supporting any unstable ground around the open-

ing while requiring the ejection of only the inner section of the cutterhead. The main disadvantage is that the hollow machine must be of larger diameter.

e. Minor Requirements

Most headings require high pressure air, water, ventilation, and electrical power. Elimination of one or more of these will simplify heading advance since they must also be extended 25 feet each hour.

High pressure air is generally required for tools and machine maintenance but can be supplied with an onboard compressor.

An electrical power supply is a necessity to drive the machine and provide lighting. High voltage motors could be used to eliminate the need for a large transformer. Cable reels or coils can be used to reduce the number of connections in the main power cable.

A supply of water is generally required as a coolant for hydraulic oil and is sprayed on the face to reduce dust. In this operation, it might also be used to aid in muck flow by being forced down the invert or used as a coolant for the main drive motors. This would reduce their overall dimensions and possibly reduce the tunnel diameter required.

Egress Machine Description

Figures 17 through 19 illustrate two approaches to the tunneling system. Figure 18 shows a small diameter machine, all of which is ejected from the tunnel; Figure 19 shows the larger diameter machine which requires removal of only the inner cutterhead.

The approaches are basically similar. Both machines mine uphill and both have a gripper system directly behind the cutterhead support. They each have a six piece, full circle lining installed manually behind the cutterhead support. In either case, the missile can be towed behind the machine or brought up just prior to hole-through.

FIGURE 17 is a foldout and appears at the back of this book.

FIGURE 18 is a foldout and appears at the back of this book.

FIGURE 19 is a foldout and appears at the back of this book.

A clear path for missile launch is achieved by pushing out the entire machine in one case or by pushing off the inner cutterhead in the hollow machine.

The missile transport car must allow passage of men, materials, and lining plate. It is shown to be self-propelled and provides the upper anchor point for the supply car hoisting cable. This car could also be self-propelled.

The ventilation system could be a pressure system with tunnel air forced out at the portal. This should be possible since no muck haulage system exists and if the lining joints are adequately sealed. This allows a lightweight flexible type of vent duct to be used to facilitate heading advance. An air scrubber should be mounted at the portal to clean the exiting air if required.

Possible Machine Specifications

15-Foot Diameter

- | | |
|---------------------|--|
| 1. Horsepower | 1900 |
| 2. Thrust | Approximately 800,000 lbs nominal |
| 3. Cutters | 14-inch diameter change from inside cutterhead 30,000 lbs each |
| 4. Cutterhead | Approximately 10 rpm |
| 5. Muck Removal | Gravity flow through front support |
| 6. Special Features | Gripper around cutterhead support. Cutterhead support slides in gripper. Steering carried out at rear. Low force gripper also at this point. |

19-Foot Diameter

- | | |
|---------------|--|
| 1. Horsepower | 2500 hp |
| 2. Thrust | Approximately 900,000 lbs nominal |
| 3. Cutters | 14-inch diameter change from inside cutterhead 30,000 lbs each |

- | | |
|---------------------|--|
| 4. Cutterhead | Approximately 10 rpm |
| 5. Muck Removal | Gravity flow through front support |
| 6. Special Features | Gripper and steering occurs around front support |

Costs and Operating Factors

- | | |
|--|---|
| Estimated Capital Cost (15-ft diam.)
(heading machine only) | 1.5 x normal - budget \$3.6M |
| (19-ft diam.) | 1.5 x normal - budget \$4.8M |
| Penetration Rate Target | 25 ft/hr coverage |
| Utilization Target | 84% |
| Assumed Ground Conditions | <ol style="list-style-type: none"> 1. Rock strength = 6,000 psi 2. Depth = 2,400 ft |

CHAPTER 4

EGRESS MACHINE JARVA CONCEPT

The concept of a tunneling machine for post-attack egress designed by Jarva, Inc., has special features to permit excavation through fractured rock of the type which will be encountered between an underground missile station and the rubble zone.

The following information was furnished by Jarva, Inc., in a letter of transmittal dated April 16, 1979:

The conceptual drawing (Figure 20) is of a TBM which may be suitable for use as the egress machine in the Deep Base Missile Program.

It is anticipated that the machine would operate in "mesa type" terrain in soft dry rock, such as sandstone or tuff. Rock samples obtained from large boulders in the Grand Mesa Canyon were tested by Colorado School of Mines and indicate compressive strengths of approximately 6,000 psi, and linear cutting results show approximately 0.4-inch penetration of a 12-in. 75° cutter at a 3-in. spacing.

It was stated in the Tunneling Technology seminar for Deep Underground Military Facilities conducted by the Defense Nuclear Agency last October 4 that a preliminary estimate of dig-out requirements includes a maximum start-to-finish time interval of 10 days for one-half to 1 mile length of 15-ft diameter tunnel, which works out to be 11 to 22 ft/h rate of advance of the TBM, assuming it operates 24 hours a day non-stop for 10 days.

Another requirement would be to accomplish dig-out excavation through attack damaged rock.

The TBM shown on the drawing provides the features needed. They are:

1. The machine can advance continuously without having to reset its clamp legs in good rock. This is accomplished by alternately clamping the

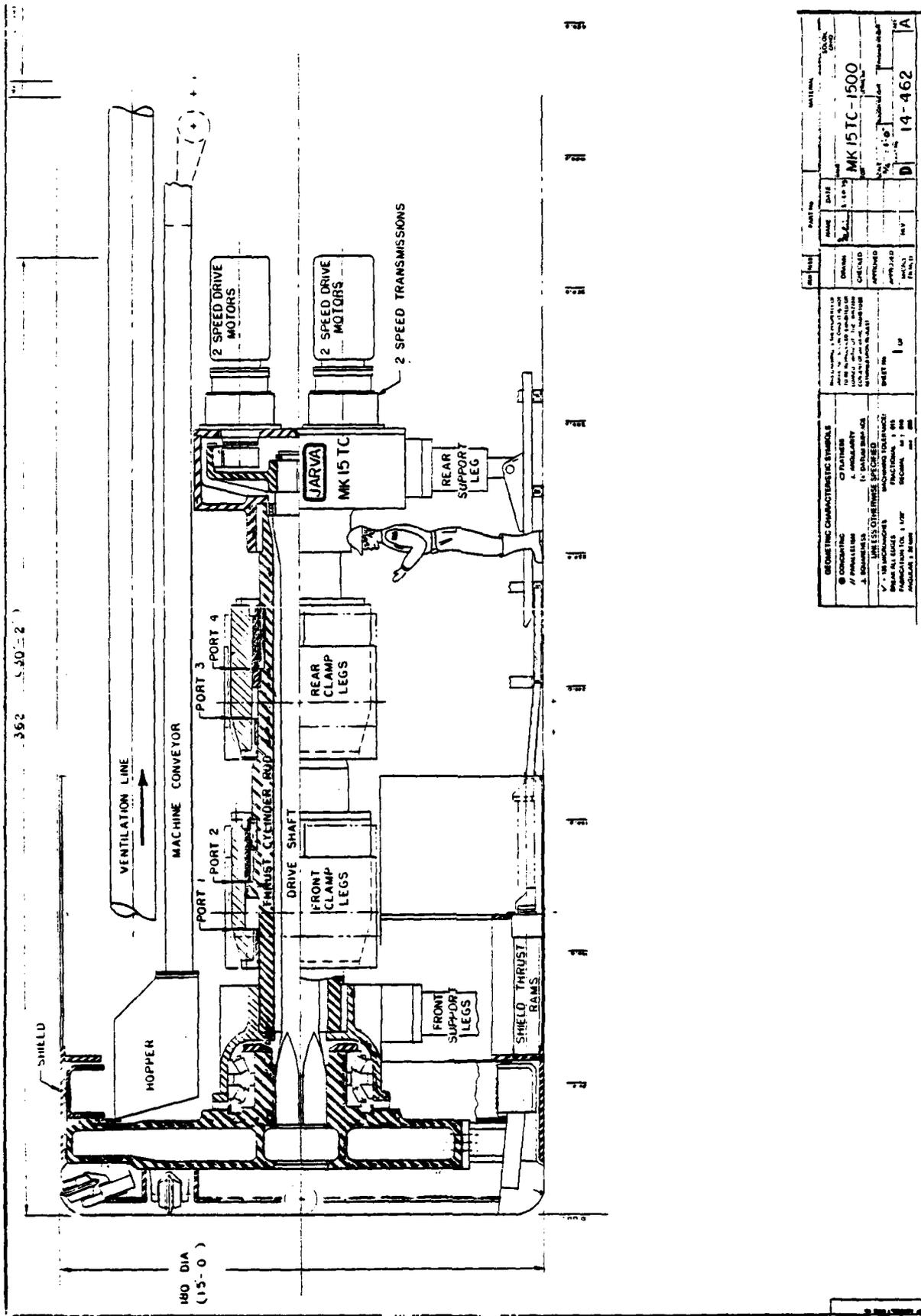


FIGURE 20 - Jarva Egress Machine Concept

machine in with either the front clamp legs or the rear clamp legs while the thrust is obtained from the piston within the clamp leg section. When one set of legs is gripping, the other set is advancing to regrip itself in the new position.

When I apply the "Predictor Equations" to this TBM with 25,000 lbs/cutter on a 15-1/2-in. 60° disc at 5-in. spacing, I get over 30 ft/h.

Therefore, I would conclude that with further testing of the rock and in the knowledge gained in driving the perimeter tunnels, the requirements of 1/2 to 1 mile in 10 days is not outside the realm of possibility.

2. In the rubble zone, the machine can advance by thrusting itself off the tunnel support linear, such as ribs and lagging as shown as conventional shields do. At this time, the clamp legs would not be used other than to stabilize the machine and prevent roll. The back of the machine would be supported by the rear support leg.

The cutterwheel would be equipped with a false face similar to one used on Jarva's MK15-1503 (Figure 21).

The cutterwheel rpm could be reduced from 10 rpm to maybe 2-1/2 rpm to get 4 times normal torque for increased power to drive through the rubble. The cutterwheel could be made to operate either clockwise or counter clockwise to correct for roll (see Jarva Machine S1907W) (Figure 22).

If the operators of the TBM are experienced with this machine in the rock of the mesa, then the required advance rates are realistic. Hopefully, the crews will be as well trained as fighter pilots and kept in top notch readiness by driving practice tunnels, for only with well practiced crews can this goal of 1/2 to 1 mile in 10 days be accomplished.

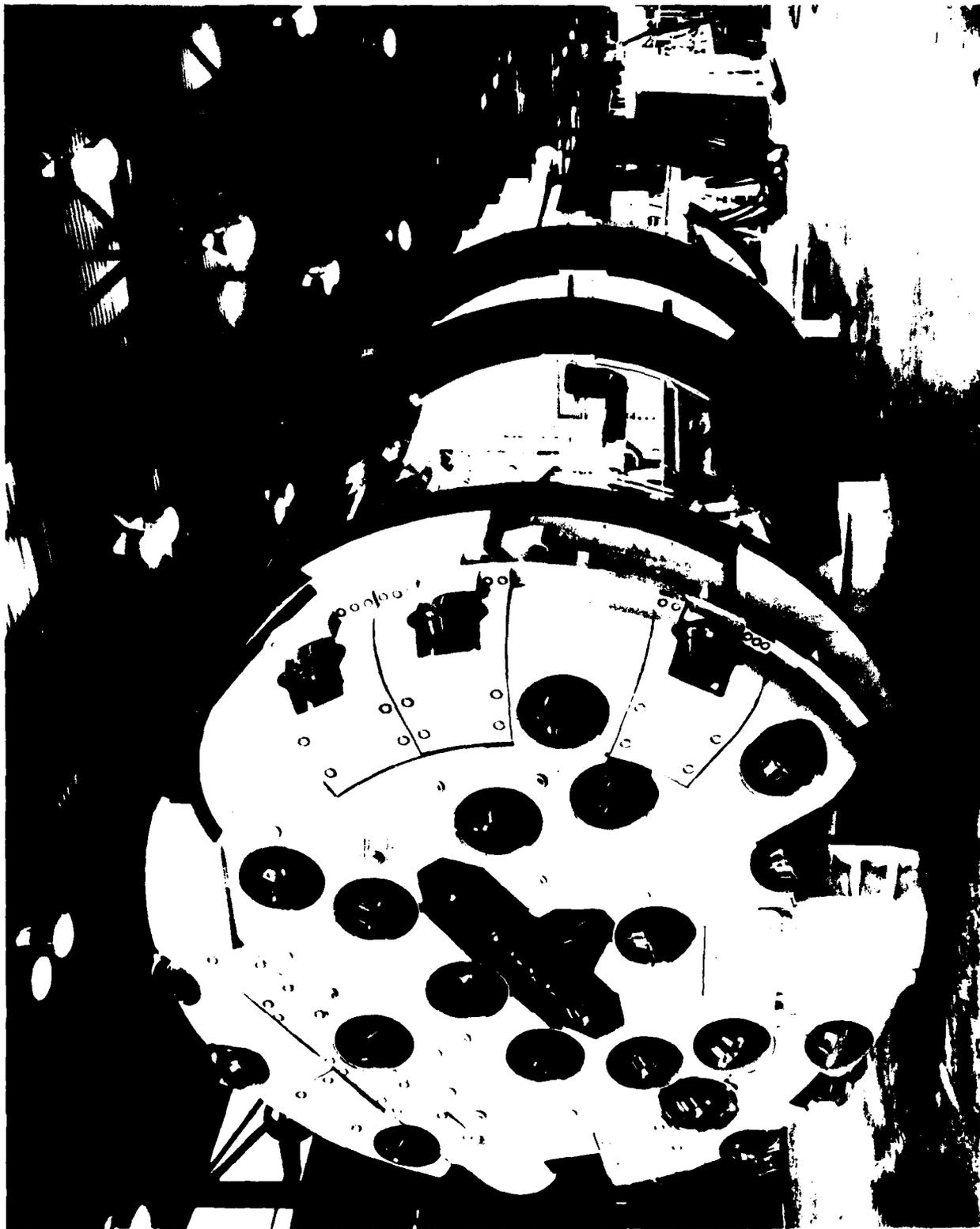


FIGURE 21 - Jarva Standard Tunnel Boring Machine

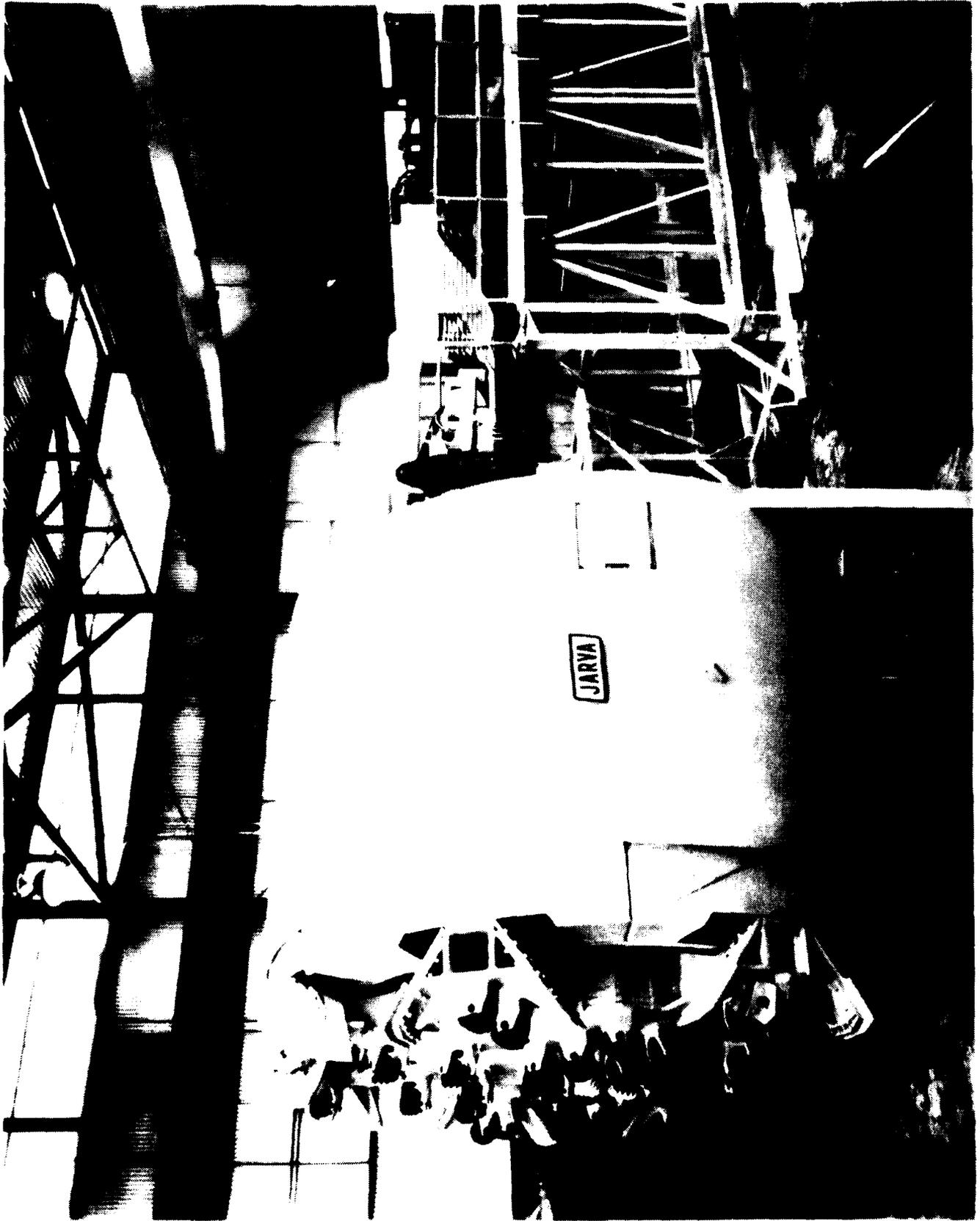


FIGURE 22 - Jarva Boring Machine with Shield

Tentative Specifications Jarva MK15TC-1500:

Bore Diameter	15 ft
Cutterwheel Horsepower	800 hp
Thrust	800,000 lbs
Cutterwheel rpm	10/5/2-1/2
Cutting Stroke - Machine Shield	Continuous - alternate re- clamping shown every ft; 4 ft shown, could be made as required
Number of Cutting Discs	35 based on 3-inch spacing - could be as low as 23 based on more rock testing

The specifications listed are only preliminary and would be revised as more testing is done.

CHAPTER 5
TUNNELING REQUIREMENTS*

General

The requirements for mechanical excavation systems to bore the unusually great length of tunnels required for the DBM system and for egress through rock which has been affected by nuclear attack are basically the same as for similar ground in conventional tunneling. However, the completion of over 300 miles of tunnel plus the excavation of openings at each missile site underground within a period of five years after beginning of excavation would require more contractors, personnel, and equipment than are currently available in the U.S. With proper planning, it is expected that equipment can be manufactured, personnel trained, and contractors recruited to complete the project.

The overall costs and logistic requirements are dependent upon geotechnical characteristics of the site, including the depth of tunnel and the topography plus the geographical location with respect to power sources, sources of labor, materials, and related factors.

Several somewhat similar methods of quantifying the geological factors which affect excavation and support requirements (Appendix A) include the RQD, joint spacing, rock strength, weathering, alteration, faulting, and other properties and structural features of the rock mass. The rate of advance and consequent costs per foot of tunnel are dependent upon the penetration rate, the advance rate of the machine, including downtime, and the time required for installation of support systems if the installation of rock support affects the overall advance rate.

*Consultation conference with Jack Leonard, Vice President of Engineering Division, Morrison Knudsen, Plaza 2, Boise, Idaho 83729.

Penetration Rates, Advance Rates, and Support for Mesa Verde Rocks

Possible advance rates were estimated by Jarva, Inc., (Chapter 4) to be as high as 30 ft/hr, which also appears to be in a reasonable range for relatively intact rock based upon the cutter tests performed at CSM (Chapter 2) for sandstones from the Mesa Verde formation. This rapid rate of advance is based upon a low percentage of downtime normal to a high efficiency of machine operation. However, the time required for support installation must also be considered.

The following examples are instructive. First, if the tunnel depth is assumed to be over 2,000 feet with a lithostatic pressure of one psi per foot of depth, the stress concentration factor for a tunnel of circular cross section is three. Hence, if the unconfined compressive strength of the rock is 6,000 psi, which is approximately the highest strength of the intact rock tested, then some type of support will be required throughout the whole of the DBM tunnel system. If complete support is required, then it is probable that the time required for the installation of the support will determine the rate of advance. The geologic columns of the Mesa Verde and similar formations which might be considered for the site of the DBM system usually consist of inclined interbedded sandstone and shales. Where shales are encountered in the tunneling operations, they will require substantial support, especially if the rock is wet.

Second, the rocks which were tested (Chapter 2) for this project had lain on the surface and had been subjected to very long term stress relief and weathering. Hence, it would be expected that similar rocks at depth would be more compact and have higher strength than those which were tested. Assuming that in situ rock at depth has an unconfined compressive strength of 10,000 psi, support would be required for nominal static condi-

tions only in zones where shale occurs or the rock is highly jointed, altered, or fractured by faulting action, i.e., where the RQD is 75% or lower. However, most of the Mesa Verde sandstones are jointed and cut by faults of various types and magnitude and hence would require some support, probably rock bolts with wire mesh and shotcrete. Sections of the tunnel where shale, intense fracturing, or jointing occur will require concrete support, probably precast concrete segments.

Where the rock is reasonably competent, the rate of advance will also depend upon the stand-up time (Figure A1; Appendix A), i.e., how soon the rock requires support after the tunnel is excavated.

Tunnel Specifications and Requirements

Following are important logistic factors for the DBM tunnels with material, labor, and other requirements for operation.

Length	50,000 l.f.
Diameter with steer tolerance	15.33 ft
Face areas	184.6 s.f.
Volume per feet	6.9 c.y.
Swell factor	1.8 to 2.0
Volume - loose	12.4 to 13.8
Sustained penetration	15.0 ft/hr
Volume per hour	186 to 207

Set up train for 5 ft of tunnel - vol/train 62 to 69

Use 10 - 7 c.y. cars/train
Need 3 trains under belt/hour

Travel to shaft - $50,000 \div 380 = 57 \text{ min} = 60 \text{ min}$
One hour in-one hour out = 2 hours + 20 min to load =
2.33 hour cycle at max. haulage - trips/hour = $60/140 = .43$

With a requirement of 3 trains per hour under belt - No. of trains req. = $3 \div .43 = 7-10$ car trains. Trains added as dist. req. - Note: With 20 min loading time, switches cannot be over 10 min apart or 8,800 ft

Ventilation required for this many locomotives?

Could require fans @ 2,000 ft with transformers

Tunnel Supplies & Equipment:

1. Mole - 800 hp	\$2,000,000
2. Trailing conveyer	300,000
3. Dust system	40,000
4. California switch	50,000
5. Muck cars - 80 ea x \$7,200 ^a	576,000
6. Locomotives - 10 ea x \$70,000 ^b	700,000
7. Dumping equipment	?
8. Hoisting equipment	?
9. Rail - 60# ASCE - 24 ga - 1000T @ \$200	200,000
10. Switch material - 20% of above	40,000
11. Spikes - 365/keg @ \$80/keg	20,000
12. Bolts - 100/keg @ \$80/keg	16,800
13. Angle bars - 1 pr/jt @ \$27.80/pr	100,000
14. Gage rods - 5,000 @ \$10	50,000
15. Hardwood ties - 6 x 8 x 4 bev. \$210/m	70,000
16. 4-in. water - 30 ft - 50,000 ft @ \$1.50	75,000
17. 6-in. air - 30 ft - 50,000 @ \$2.50	125,000
18. 8-in. disc - 30 ft - 50,000 @ \$3.10	155,000
19. 4-in. vic. coup. - 1,800 @ \$6.80	12,240
20. 6-in. vic. coup. - 1,800 @ \$12.50	22,500
21. 8-in. vic. coup. - 1,800 @ \$20.00	36,000
22. 1 tee and valve ea 500 ft	
23. Inline valves ea 1,000 ft	
24. Roof bolts - .42/ft	
25. Plates - .53/ea	
26. Nuts - .90/ea	
27. Epoxy - 12 inches - .53/ea	
28. 1-in. hose x 50 ft coupled - \$110/ea	
29. 2-in. hose x 50 ft coupled - \$295/ea	
30. Pipe hangers - every 15 ft x \$10/ea	
31. Cable hangers - every 15 ft x \$6/ea	
32. 36-in. vent line - 50,000 ft x \$10.00	50,000
33. 36-in. couplings - 1,700 ea @ \$36.00	61,200
34. 12 shp. fans - 4,000 ft int. - 13 ea	
35. Inline trans. - 13 ea @ \$11,000	143,000
36. Lights - 50,000 ft @ \$3.50/ft	175,000
37. Feed cable - 50,000 ft @ \$4.50 (13,200 r)	225,000

38.	Bulbs - 7,000 @ .80	\$ 5,600
39.	Main substation - G.F. equip.	70,000
40.	Power source	?
41.	Energy charge	?
42.	Man car	3,000
43.	Flats and utility cars	10,000
44.	Fan line car	8,000
45.	Clean up equipment	60,000
46.	Main pumps and sump	?
47.	Inline pumps	?
48.	Compressors	
49.	Shop	
50.	Office	
51.	Warehouse	
52.	Fuel storage	
53.	Change houses	
54.	IF camp - barracks and food	
55.	Water treatment	
56.	General operations	
	a. Snow removal	
	b. Road maintenance	
	c. Etc.	
57.	Overhead staff	
	a. Management and autos and super. and autos	
	b. Engineering and autos and equip. and supplies	
	c. Account	
	d. Safety and supplies and equipment	
58.	Repair parts and labor	
59.	Dep. or climate - winter heat	
60.	Equip. op. expense - fuel, oil, grease, minor repairs	

Tunnel Crew - 22 ft Tunnel - 24,000 ft - 1978 (Chicago Rates):

S = Salaried

O = Operators

L = Laborers

Day Shift

SC = Subcontract

Walker	S	1	16.25
Shift Boss	L	1	10.05
Mole Operator	O	1	12.40
Mole Oiler	O	1	9.00
Mole Mechanic	O	1	12.40
Belt Operator	O	1	11.85
Motorman	O	3	11.25
Dump Operator	O	1	12.40
Main Conveyor	O	1	11.65
Compressor	O	1	9.80
Man Hoist	O	1	11.10
Crane Operator	O	1	12.20
Loader Operator	O	1	12.20
Electrician	SC	1	23.46
Engineer	S	1	8.125
Shop Mechanic	O	2	12.20
Miners	L	2	9.55
Laborers	L	3	9.425
Bottom Man	L	1	9.425
Top Man	L	1	9.425
Bull Gang Boss	L	1	10.05
Bull Gang	L	2	9.20
Track Man	L	2	9.425

All operators receive an additional 0.20 for underground, which is included in rate. Swing shift operators receive an additional 0.25 and graveyard operators receive an additional 0.50. Both are included. Salaried personnel receive 2 weeks' paid vacation. Rates are as follows: Hew = 1.10; Pen. - 1.10; Val. - 0.60; Apprent. - 0.05. Laborers' total fringes - 1.68. workmen's Comp. - 18.5%. Fed. Unempl. Tax - 0.7%. State Unemployment = 4.00%. FICA - statutory rate - 6.55%. PL & PD = \$1.83/100.00 of contract.

Tunnel Crew - 22 ft Tunnel - 24,000 ft - 1978 (Chicago Rates):

	S - Salaried		
	O - Operator		
	L - Laborer		
<u>Swing Shift</u>	SC - Subcontract		
Walker	S	1	16.25
Shift Boss	L	1	10.05
Mole Operator	O	1	12.65
Mole Oiler	O	1	9.25
Mole Mechanic	O	1	12.65
Belt Operator	O	1	12.10
Motorman	O	3	12.10
Dump Operator	O	1	12.65
Main Conveyor	O	1	11.95
Compressor	O	1	10.05
Man Hoist	O	1	11.35
Crane Operator	O	1	12.45
Loader Operator	O	1	12.45
Electrician	SC	1	25.72
Engineer	S	1	8.125
Shop Mechanic	O	2	12.45
Miners	L	2	9.55
Laborers	L	3	9.425
Bottom Man	L	1	9.425
Top Man	L	1	9.425

Tunnel Crew - 22 ft Tunnel - 24,000 ft - 1978 (Chicago Rates):

	S - Salaried	O - Operators	L - Laborers	SC - Subcontract	
<u>Graveyard</u>					
Walker	S	1			16.25
Shift Boss	L	1			10.05
Mole Operator	O	1			12.90
Mole Oiler	O	1			9.50
Mole Mechanic	O	1			12.90
Belt Operator	O	1			12.35
Motorman	O	3			12.35
Dump Operator	O	1			12.90
Main Conveyor	O	1			12.15
Compressor	O	1			10.30
Man Hoist	O	1			11.60
Crane Operator	O	1			12.70
Loader Operator	O	1			12.70
Electrician	SC	1			26.84
Engineer	S	1			8.125
Shop Mechanic	O	2			12.70
Miners	L	2			9.55
Laborers	L	3			9.425
Bottom Man	L	1			9.425
Top Man	L	1			9.425

Sat. Main. - Mole Operator, Mole Oiler, Necess. Mechanic, Motorman, Elevator, Top Man, Bottom Man, Crane, Compressor Operator, Necess. Laborers, Electrician, all at time and one-half. Insurance is not paid on previous amounts.

Because of the uncertainty of the strength of rock and the fact that there will be highly jointed, fractured, and faulted rock and shale encountered in the excavation of the DBM tunnels (some water is to be expected); because the distance of muck haulage from the tunnel portals is unusually long; and because the depth of the tunnels is greater than that usually encountered in tunneling operations, it was estimated that the current tunnel costs for the DBM system may be as high as \$1,600 per linear foot, based on costs of similar tunnels in Chicago.

This is much higher than the base costs utilized for the COSTUN program, for which it was assumed that the 1979 costs would be \$600 to \$800 per foot based upon current tunneling costs for the Chicago Metropolitan District sewer tunnels. The latter costs may be low, but until an actual site is determined for the DBM system, there are many cost factors which cannot be determined with any degree of accuracy, such as the nearness to sources of power, the local geology, the availability of labor and machines, etc. It appears logical to assume that the 1979 costs could vary between \$600 and \$1,600 per foot, the latter figure being the most reasonable estimate.

CHAPTER 6

PROJECTED TUNNELING COSTS - COSTUN

The COSTUN computer program (Ref. 2) was designed to compute in a short time costs of tunneling for budgeting, estimates, and other purposes for ranges of several cost parameters. Typical graphs were provided for making quick estimates if values of pertinent factors are known (see Volume II of this report). Basic data related to tunnel geometry, site conditions, and other factors are required for complete calculations for a given site. Costs may be relatively insensitive to some factors, such as geographical location, but are very sensitive to the size of the tunnel and the geologic structure through which the tunnel is driven.

For the calculation of the costs of the excavation of the DBM system (exclusive of the egress tunnels through rubble), the site data are hypothetical because no specific site has been selected. However, some typical sandstones were obtained from the Mesa Verde formation and properties measured for prediction of penetration rates. The specifications for the tunnels are that they be at 2,000 to 2,500 ft deep and 15 ft in diameter, with access tunnels to the surface spaced at about 10-mile intervals. For the remainder of the factors needed for cost calculation, assumed values were used.

A summary of the specifications is:

Length of access tunnels - 2,500 ft

Spacing between access tunnels - 10 miles

Length of tunnel segments between access tunnels - 25,000 ft

-
2. Wheby, F.T., 1975, "Parameter Estimates of Costs for Tunneling Rock," Tunneling Technology Newsletter, U.S. National Committee on Tunneling Technology.

Tunnel diameter - 5 meters

Tunnel depth - 2,000 to 2,500 ft

The compressive strength of the sandstone varied from about 4,000 to 6,000 psi. The stress concentration in a circular tunnel at 2,000 ft depth would be 6,000 psi, using a stress concentration factor of three. Hence, even for intact rock, the tunnel will require lining, and the lining operations will determine the rate of advance.

Summary of Computer Input

Access Tunnel Length	2,500 ft
Segment Lengths	25,000 ft
Tunnel Shape	Circular
Tunnel Size	15 ft diameter
Excavation Method	Tunnel Boring Machine
Muck Removal Method	Rail Haulage
Rock Strength, Compressive	3,900 psi
RQD	50
Temperature	70°F
Lining	Steel Reinforce Concrete
Lining Thickness	8 inches
Hours Per Day	24
Days Per Week	6
Average Rate of Advance	59.1 ft/day Access
Average Rate of Advance	62.8 ft/day Segments

Adjustments are made to basic cost computations for inflation.

Labor adjustment was projected from labor prices in Chicago, Illinois, for the year 1969, which was based upon data in the Engineering News Record

Construction and Wage Indexes and the U.S. Bureau of Reclamation Irrigation and Hydroelectric Cost Indexes. Projections were made for two rates of inflation per annum: one for a 6% increase, and one for a 10% increase. The USBR indexes are based on average costs for 17 western states. Similar adjustments were made for the cost experience in Chicago for equipment and material.

Another cost adjustment is that due to geographical location. For Chicago, this is 0.9, and for New York City, 2.0. The costs for the DBM will be sensitive to geographical location because the site will probably be in an isolated area. Also, on this large a project, labor and machine costs would escalate more rapidly than normal. These factors were not taken into consideration in the calculations using the COSTUN program.

It is noteworthy that for 6% escalation, the costs increase by a factor of about 8 over a period of 50 years, and by a factor of 10 for a 10% annual escalation (see Figures 23-26).

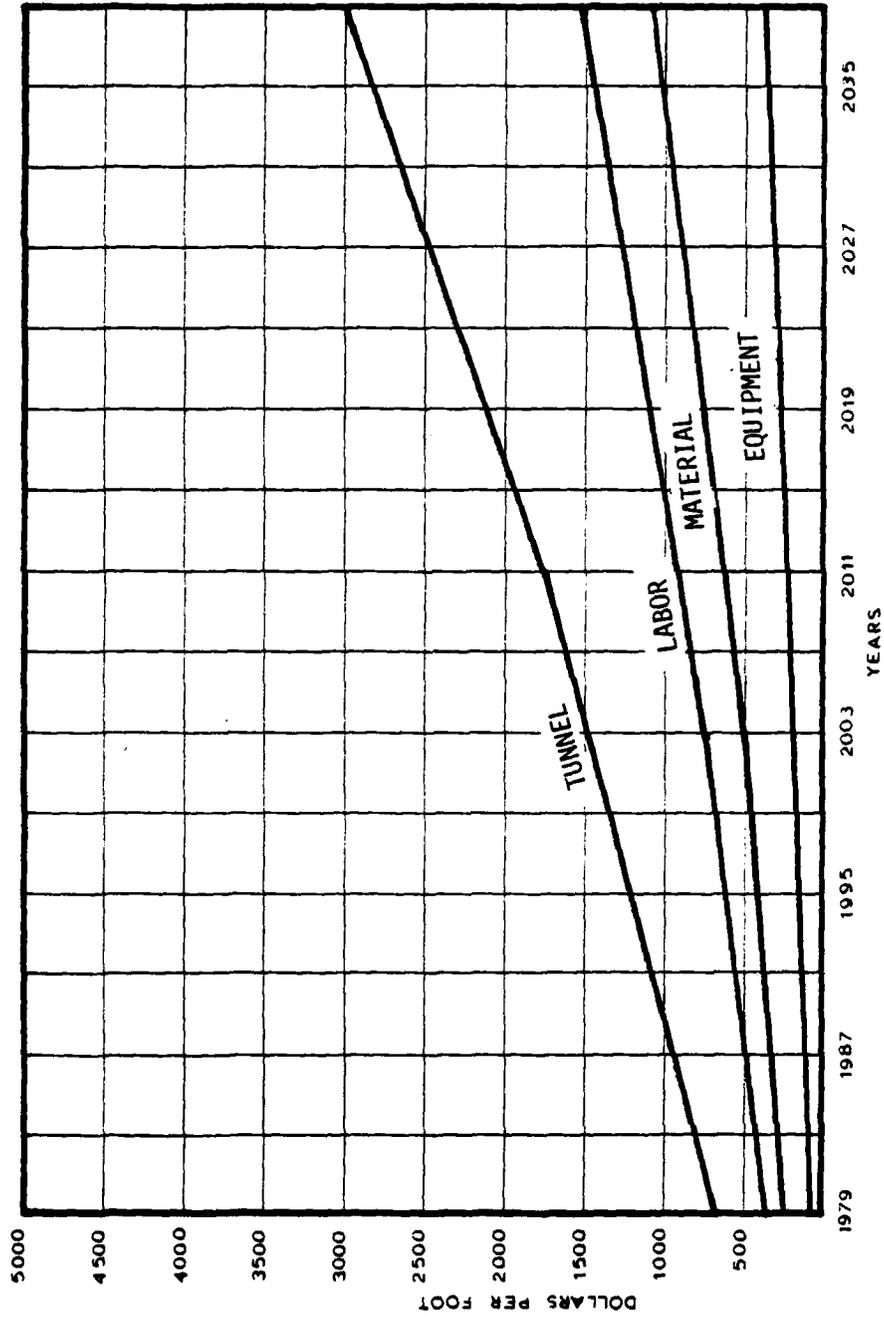


FIGURE 23. Projected Tunnel Costs for Portal Sections, 2500 ft at 6% Annual Escalation.

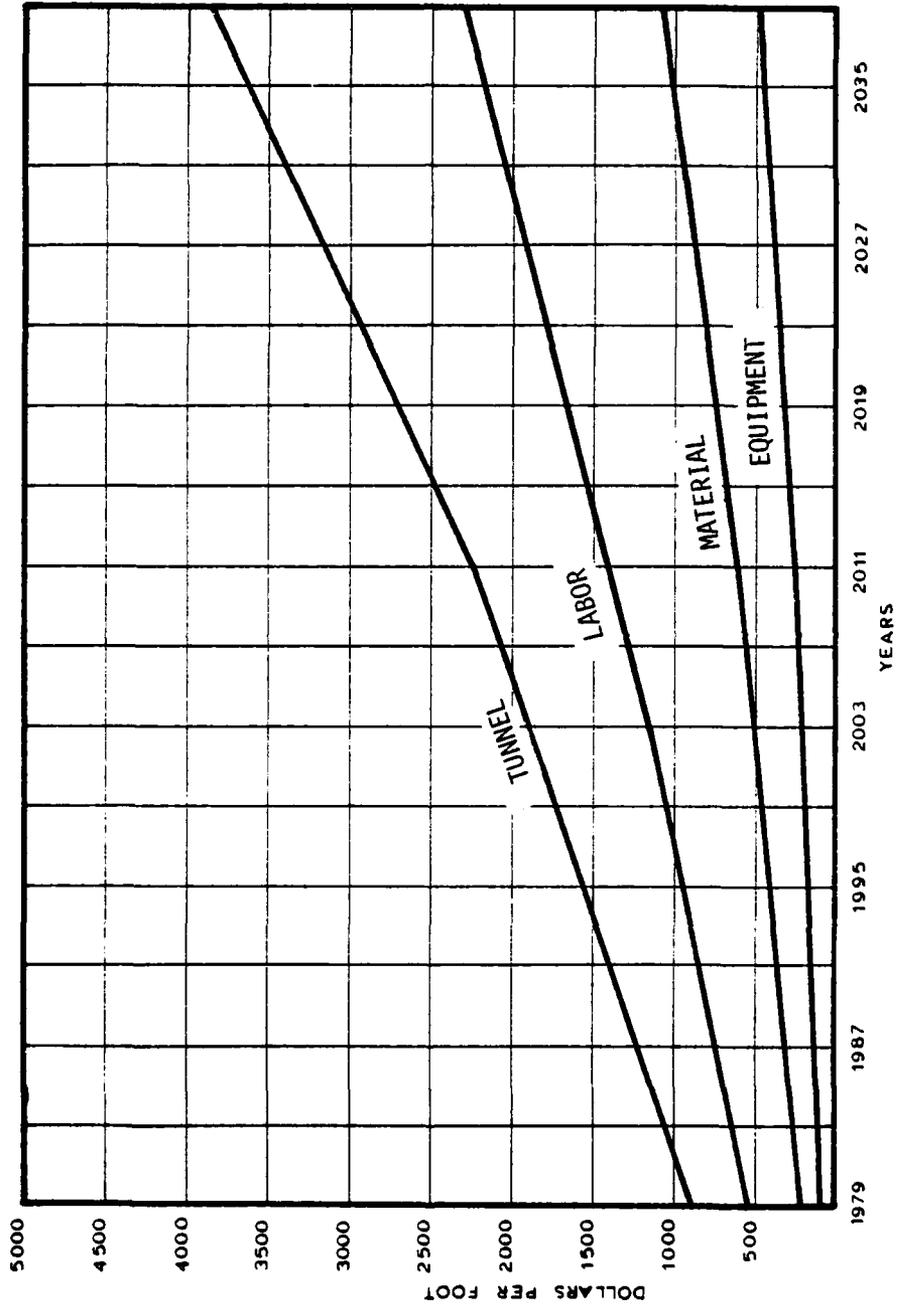


FIGURE 24. Projected Tunnel Costs for Main Section Tunnels, 25,000 ft at 6% Annual Escalation.

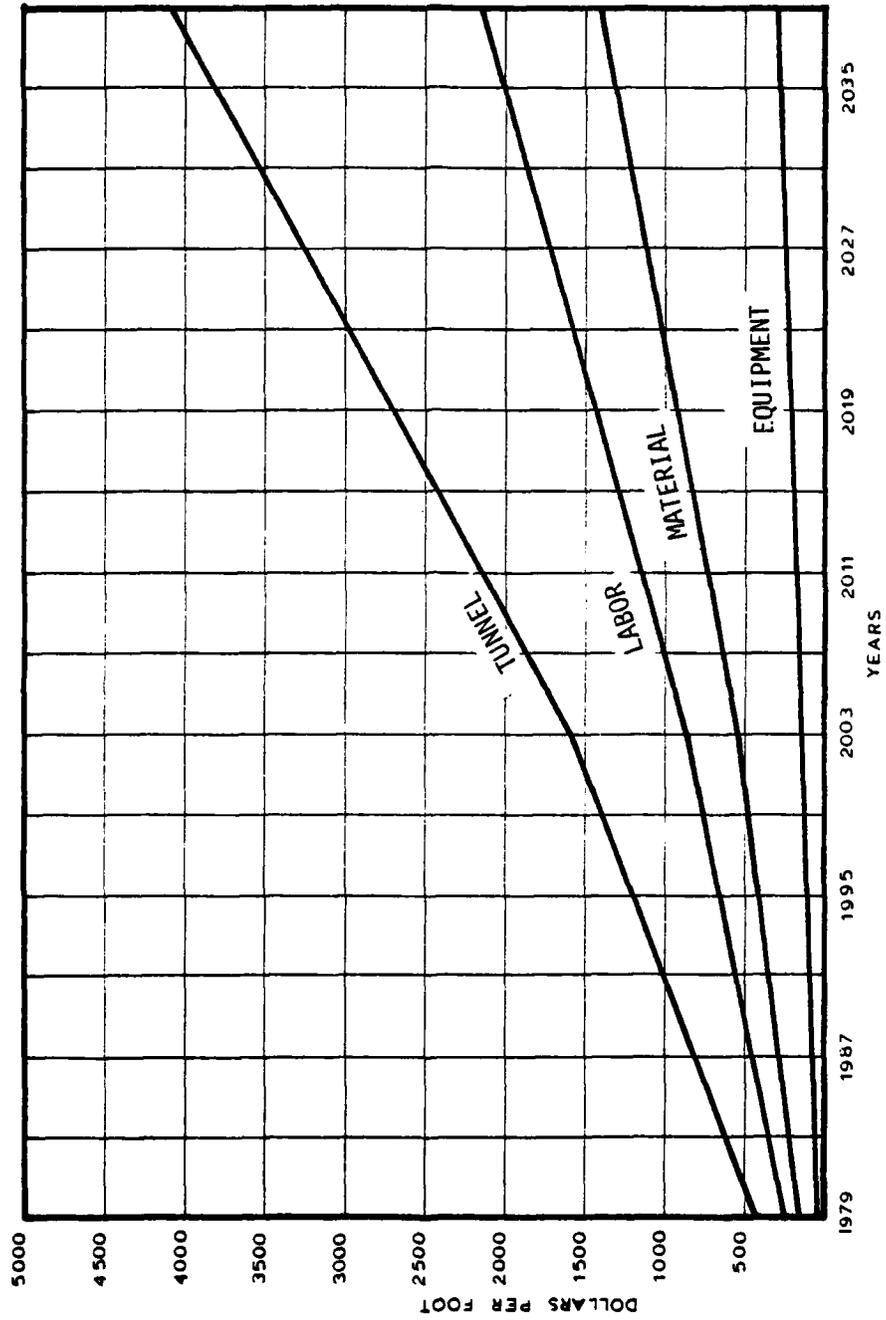


FIGURE 25. Projected Tunnel Costs for Portal Sections, 2500 ft at 10% Annual Escalation.

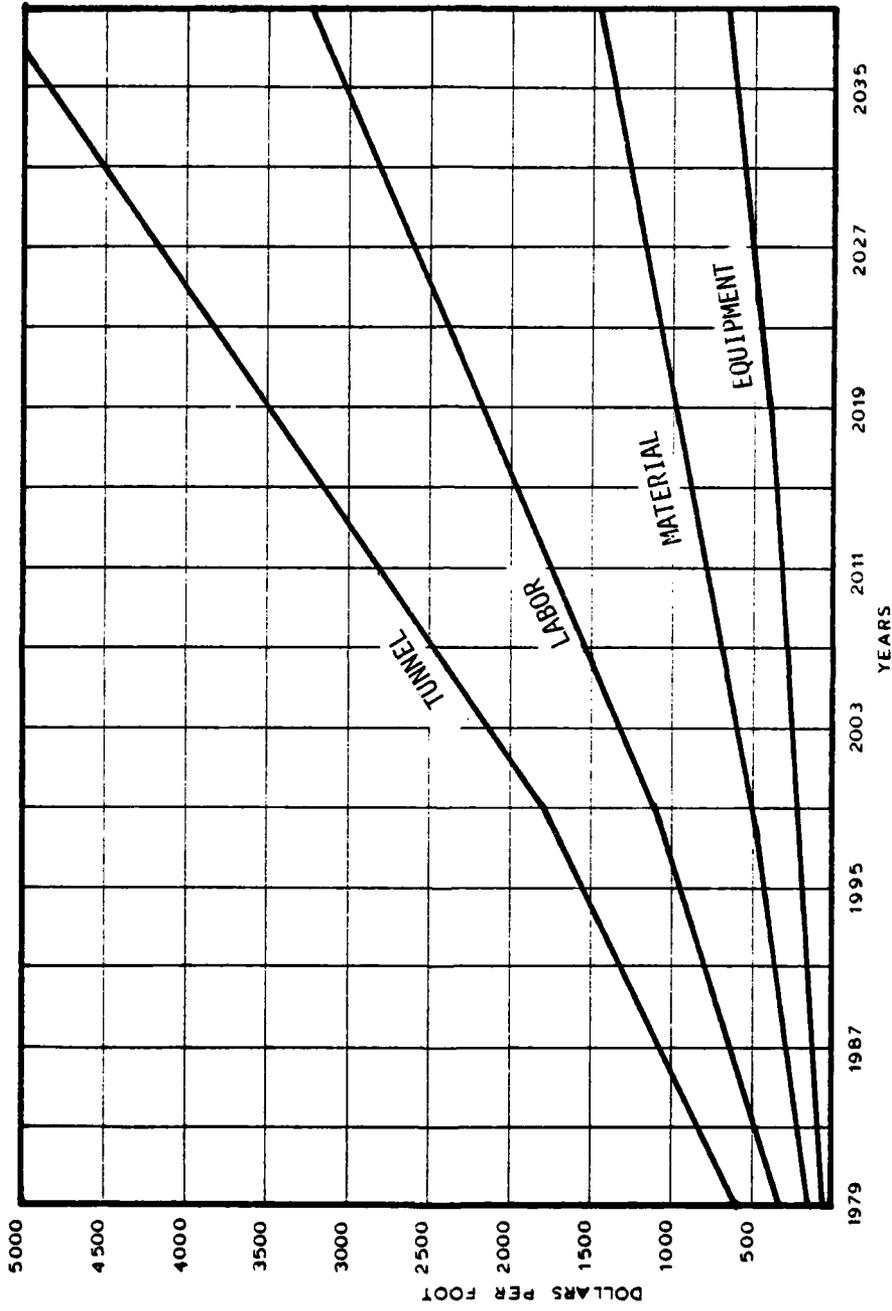


FIGURE 26. Projected Tunnel Costs for Main Sections, 25,000 ft at 6% Annual Escalation.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

From the discussions and analyses in this Volume and in Volume II of this report, the items specified for the project may be evaluated as follows:

TBM Characteristics

Tunnel boring machines may be classified according to the boreability or hardness (strength) of the rock:

1. Hard rock
2. Medium hard rock
3. Medium soft rock
4. Soft rock

These four classes correspond roughly to ranges of unconfined compressive strength, although linear cutting tests provide a better measurement of boreability. For DBM siting in sandstone or tuff in which the attenuation of stress waves is high, the rock would fall into one of the last two classes which are easy to bore when relatively intact. For very soft rock, it may be possible to use drag bits instead of roller cutters. Such a determination would need to be made for a particular tunnel site after the properties of the rocks, which will be cored, have been determined.

The major restraints on advance rate may be the stand-up time of the tunnel structure after it is excavated, the support required for tunneling through (1) competent rock, or (2) incompetent fractured rock, and (3) how the support installation operations interface with TBM operation. Also, it is certain that fault zones with gouge, highly jointed rock, and shale will be encountered by each machine as it excavates a 10-mile section of the 300+ miles of the DBM tunnel system in sandstones and associated rocks.

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COLORADO SCHOOL OF MINES GOLDEN

F/G 13/2

TUNNEL BORING MACHINE TECHNOLOGY FOR A DEEPLY BASED MISSILE SYS--ETC(U)

AUG 80 G B CLARK, L OZDEMIR, F WANG

F29601-78-C-0056

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The cutting head of the machine may be designed to cut soft to medium-soft rock with the appropriate type of cutters, cutter spacing, thrust, power, etc., but will also require a shield which can be used when incompetent rock is encountered.

The machine designs by Robbins (Chapter 3) and Jarva (Chapter 4) have incorporated the features designed for an egress operation which will be required to tunnel through the broken rock to the rubble zone. Essentially the same type of machine will be required for excavating the DBM system. These machines embody only relatively minor modifications of existing types of machines which were designed for particular tunneling projects, and the total cost of construction is determined by the specific features and specifications for the design conforming to a given geologic site. That is, each TBM is designed for a particular geologic site and excavation requirements based upon the anticipated rock conditions, i.e., for a given type of rock, a given length of tunnel for given rock structural conditions with the objective of achieving the most rapid rate of advance at the lowest feasible cost.

Thus, the designs by Robbins and Jarva described herein represent the most efficient machines which can be made available when corresponding working drawings are made and the machines are constructed, for both conventional and egress excavation in rock at a specific site. Inasmuch as machines will be designed and built for the DBM site conditions, it is not meaningful to discuss comparisons between existing types of machines that were constructed for other geologic environments.

Labor Support Requirements

The labor support requirements for a sample conventional tunnel boring project given by Leonard (Chapter 5) indicate that as many as 30 men may

be needed to operate a TBM on a day shift with about 25 men on the swing and graveyard shifts. The same number of men will be required for the operation of each TBM for the excavation of the TBM system exclusive of crews required for muck transport. At least two men are needed for each muck train with others to maintain the ventilation system, to handle supplies, and another to place the support system.

On the other hand, the egress machine will probably be operated in two 12-hour shifts with a skeleton crew of about twenty men on each shift. The supervisory personnel, the operators, and maintenance crew will require a reasonably high level of experience, skill, and expertise in the critical aspects of the operation of tunnel boring machines. One method of training them would be to have them work on the crews of the TBMs which are used to excavate the DBM tunnel system.

General project experience with the TBMs has shown that cutter replacement depends upon the abrasiveness of the rock and upon the position of the cutter on the cutterhead. Most cutterheads are designed so that the cutters are easily replaced. Routine operation in uniform rock usually requires a high level of skill, and operation in loose rock requires the same skills plus a good degree of innovative ability.

A new TBM has been found to operate for a predictable length of time depending upon the construction of the machine and the operating conditions. At the end of that period, a complete overhaul is recommended. This factor is important where the machine will be used for very extended periods of operation as anticipated for the DBM tunnels.

For the egress operations the machine reliability must be at a maximum because of the critically short time of operation and the rapid advance rates, heavy ground conditions, and the level of expertise of the crew. Hence, the egress TBMs must be of the highest quality and reliability,

even though their period of operation will be short. The experience acquired by the contractors and machine manufacturers during the excavation of the DBM tunnels where loose rock is encountered will furnish the most reliable information upon which optimum designs may be based for the egress machines.

Projected TBM Performance and Costs

The important factors which affect advance rates and costs were reported by Hamilton (Ref. 3) and Robbins (Ref. 4). These include rock boring efficiency, tunneler capability, effects of penetration rate and system utilization, penetration rate vs time and rock strength, cutter costs vs time, and effect of tunnel size (diameter) and have been extended to the year 2010 (Figures 27 to 33).

The major advances during the past decade have been due to increased penetration rate and increased machine availability. The factors are interdependent and the improvements have resulted from improved cutter and bearing performance, improved machine design, and better understanding of the effects of rock structure and properties upon the boreability of rock. For incompetent rock, the improvements in methods of rock support immediately behind the TBM has contributed to increased machine availability and consequently to better advance rates.

A reasonable projection of the trends described by Hamilton and Robbins indicates that the effects of all categories of improvements have rapidly leveled off or will do so in the very near future. This leads to a quite

-
3. Hamilton, W.H., 1972, "Role of the Tunneling Machine," Proc. RETC, p. 1093.
 4. Robbins, R.S., 1970, "Development Trends in Tunnel Boring Machines for Hard Rock Application," 1st U.S.-Sweden Underground Workshop, Stockholm, 1976.

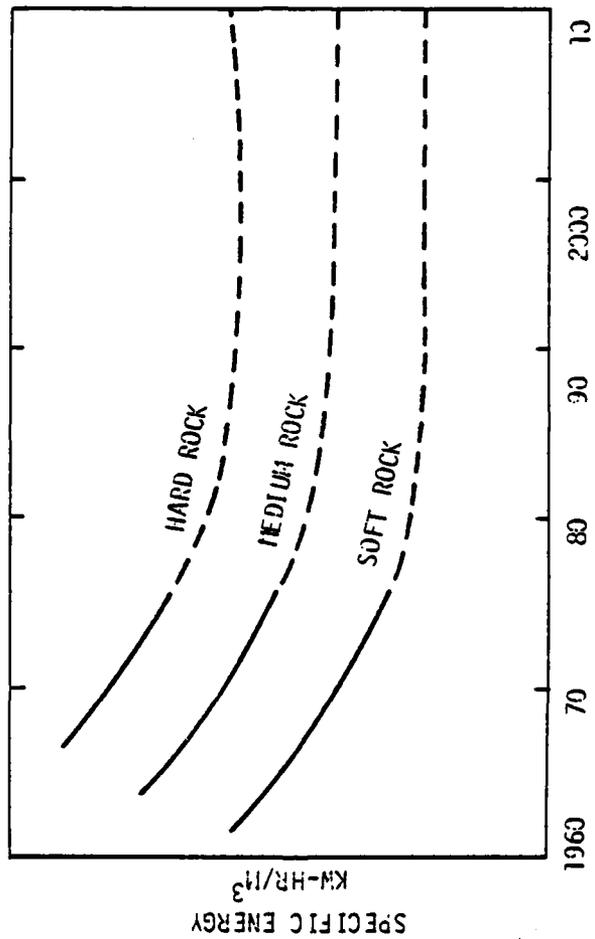


FIGURE 27 - Rock Boring Efficiency - Projected (after Hamilton, 1972)

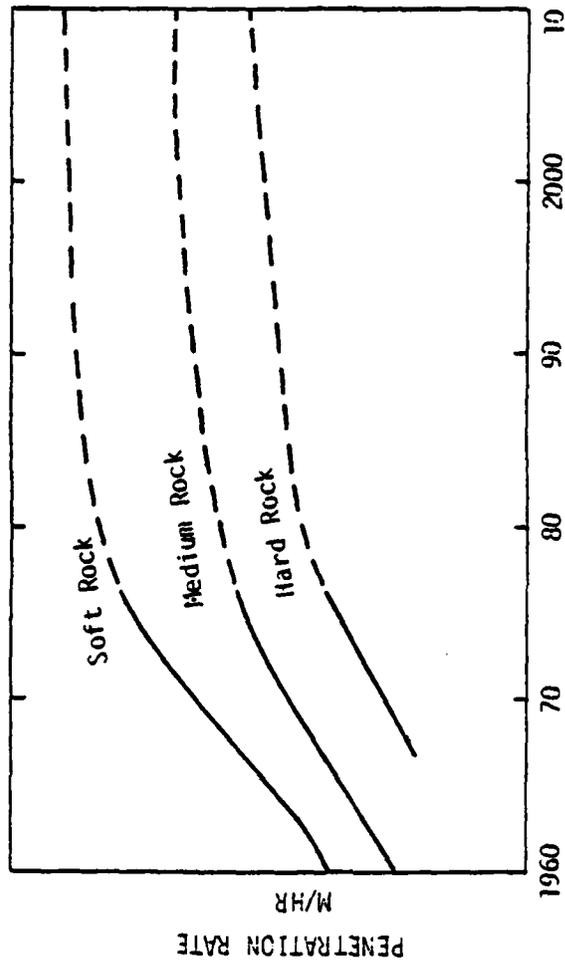


FIGURE 28 - Tunneler Capability - Projected (after Hamilton, 1972)

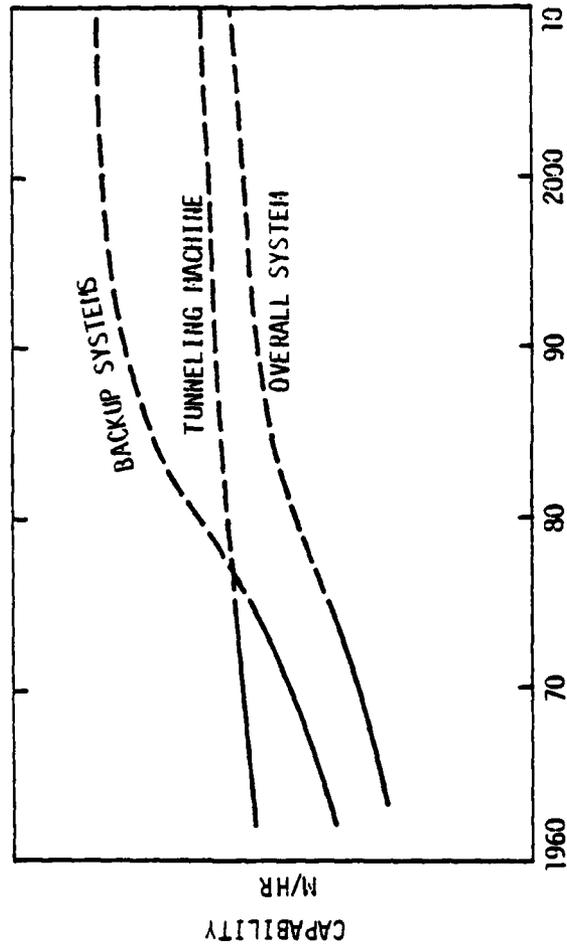


FIGURE 29 - Overall System Capability - Projected (after Hamilton, 1972)

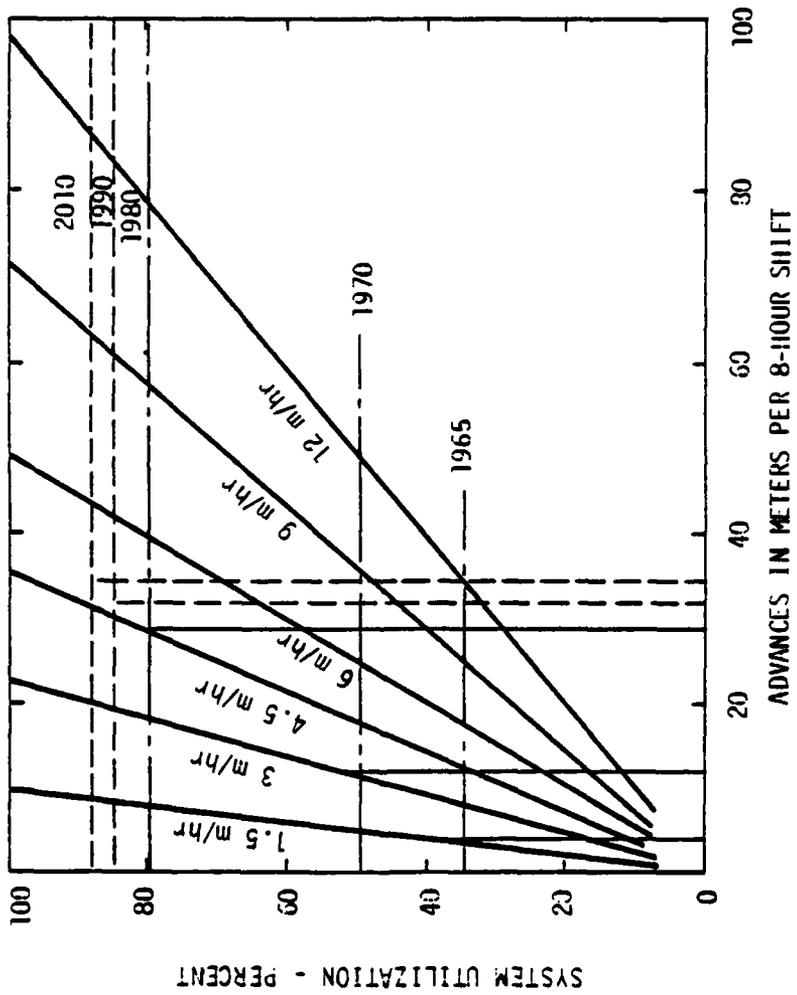


FIGURE 30 - Effect of Penetration Rate and System Utilization on Advance Rate - Projected (after Hamilton, 1972)

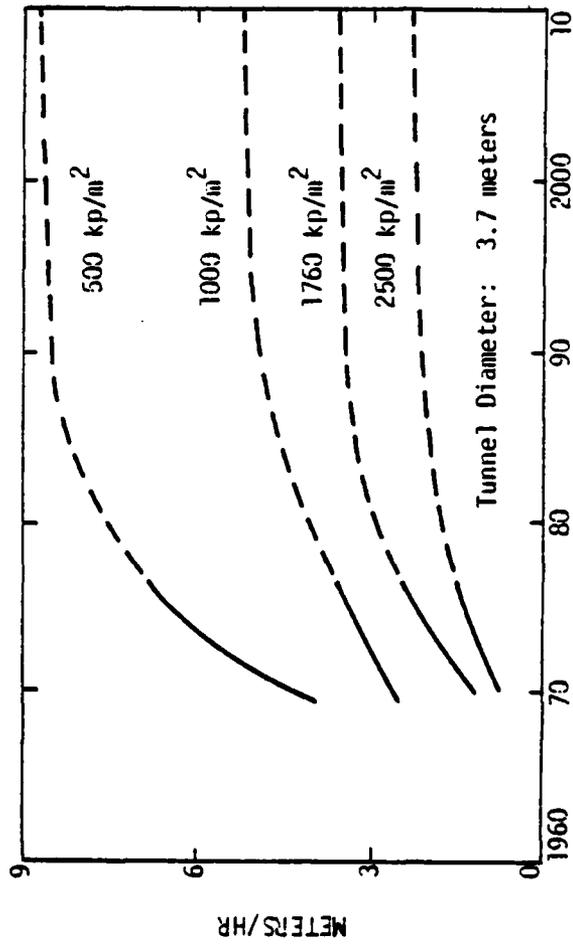


FIGURE 31 - Penetration Rate vs Time Showing Effect of Rock Strength - Projected (after Robbins, 1976)

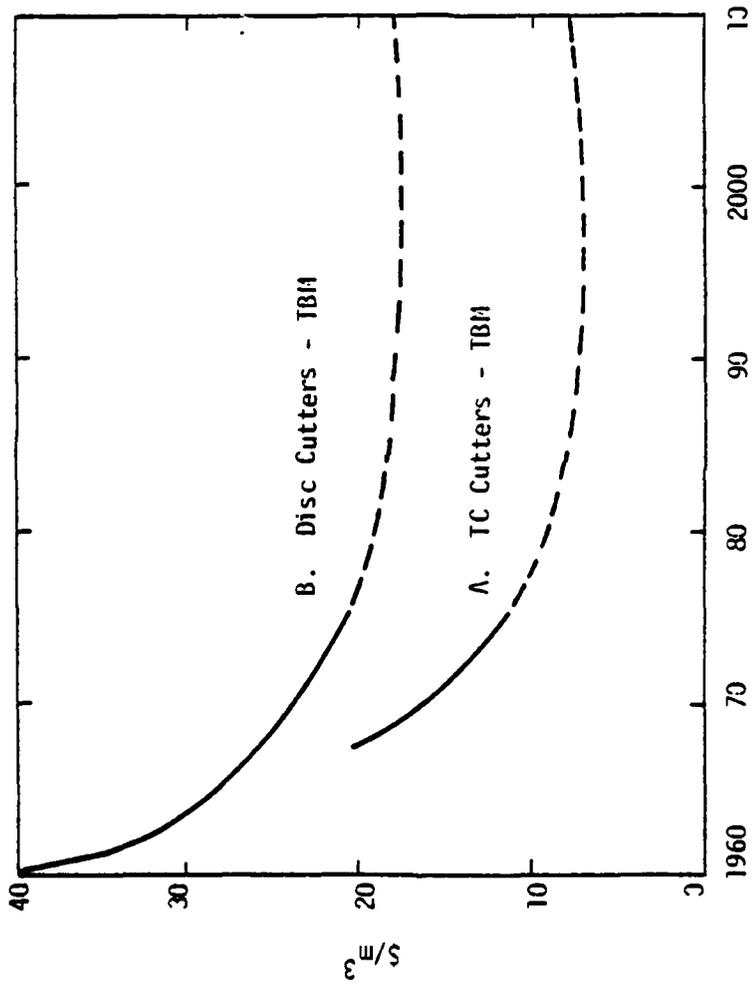


FIGURE 32 - Cutter Costs (1976) vs Time - Projected
(after Robbins, 1976)

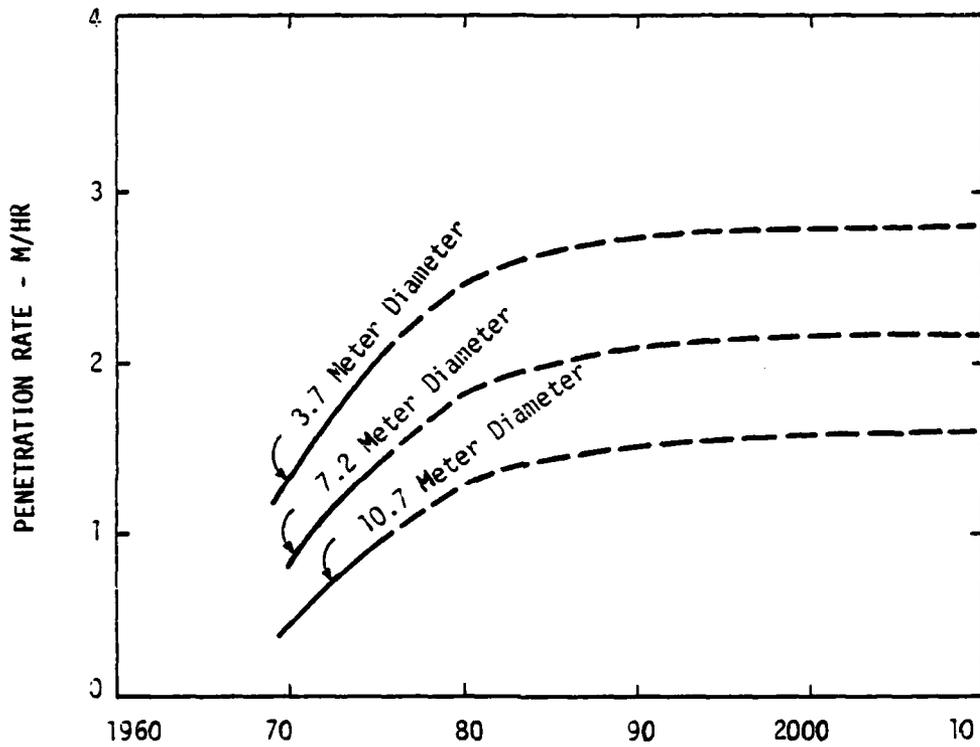


FIGURE 33 - Penetration Rate vs Time; Showing Effect of Tunnel Size in Rock of 1760 kp/cm² (after Robbins, 1976)

firm conclusion that there will be no significant lowering of costs or increases in advance rates in the near future. One possible exception to this would be the successful application of high pressure water jets as an assist in cutting, particularly in soft rocks such as sandstone. However, the application of water jets to tunnel boring is still in the experimental or development stage and has not yet been established as a practical operation.

Another important factor that results in an overall restraint is the removal of muck from the TBM and its transportation to the surface. This problem increases in its effect on advance rates and costs as the distance from the tunnel face to the portal increases. There is a practical limit to the number of cars per train, the number of trains per tunnel face, and the number of bypasses in the rail system, all of which are related to the length of travel from the tunnel face to the surface. As indicated above, another critical factor is the stand-up time of the tunnel opening and the type of support required. If immediate support is needed, then the rate of tunnel advance is determined largely by the rate at which the support can be installed. Thus, the length of muck haulage and the type of tunnel support can be major factors in determining the costs per foot of tunnel.

In the choice of a site or sites for a DBM system, it is expected that there will be a limited number of locations which will be suitable from a geological point of view, and geographical and political considerations will probably reduce the possible choices to perhaps as few as one or two locations. In this case, the tunneling operations must be adapted to the site, rather than choosing a site which has the best conditions for ease of tunnel excavation.

TBM Tunneling Variables

All of the factors which affect the efficiency and cost of tunneling have been described in detail in Volumes I & II of this report. The ideal geologic environment will be a massive sandstone or tuff of about 15,000 psi unconfined compressive strength with a minimum of joints, faults, bedding planes, and with little or no shale (in sedimentary rocks) or water.

A practical optimum geological environment will include the following, in approximate order of importance:

Rock Type: sandstone or tuff, with a minimum of shale

Structure: massive or horizontal beds, uniform

Strength: about 15,000 psi unconfined compressive strength

Faults: minimum number with small displacement and narrow zones of fracture

Joints: minimum number, widely spaced

RQD: high, about 80%

Boreability: easily bored

Water: minimum or none

Most of these factors are interdependent, and hence, a prioritized list must be considered in terms of local conditions of a given geological site.

Cost and Design Trade-Offs - Egress Machine

As described earlier the most productive approach to the design and construction of the most effective egress machines will be to base the design upon the experience gained in the process of tunneling through the loose rock encountered in the excavation of the DBM system.

The specifications for a conventional TBM to mine through unstable ground are (1) a high degree of reliability, (2) simplicity of operation, (3) ease of repair and replacement of parts, (4) flexibility in interfacing with support installation operations, (5) ability to tunnel through very

unstable ground, (6) handling of water, (7) facility of muck disposal, and (8) optimization of other related operational factors. For a tunneling contractor, all of these items are critical if he is to meet tunneling schedules and estimated costs.

For the operation of an egress machine by a military crew, the critical factors for successful excavation are virtually identical with those which are important in conventional tunneling. Unless the crews are trained as well as civilian crews, then a greater degree of reliability may be required for the egress machines. Thus, a reasonable conclusion is that there will be few trade-offs in the egress TBM proper. If the Robbins concept is used, there would be some savings in the conveying and mucking system and possibly less interference with the installation of support systems behind the TBM as it advances.

The machine must be capable of tunneling through ground with a low RQD of about 50, assuming that the rock fragments are not friable and have a fair degree of cohesion. An estimate of the relationship between the RQD and the TBM advance rate (Figure 34) indicates that extreme difficulties would be encountered in rock which had an RQD much below 50.

Thus, the egress machine should be designed to operate under the most difficult conditions for a maximum penetration rate. This will mean that bearing and cutter design must be optimum, no sacrifices can be made in the strength of the body of the TBM, power requirements cannot be reduced, nor can other compromises be made in design. The probable lower level of training and expertise of the military crew will mean that all controls, parts of the hydraulic system, etc., must be of maximum reliability and ease of operation.

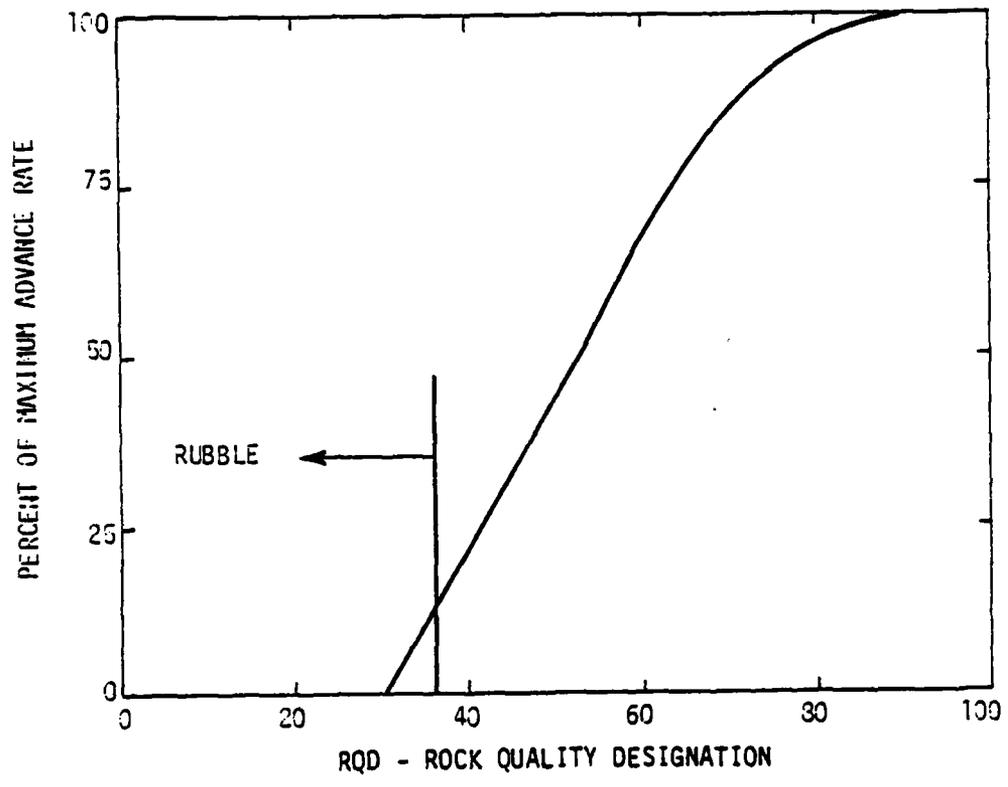


FIGURE 34 - Approximation of Effect of RQD on Advance Rate

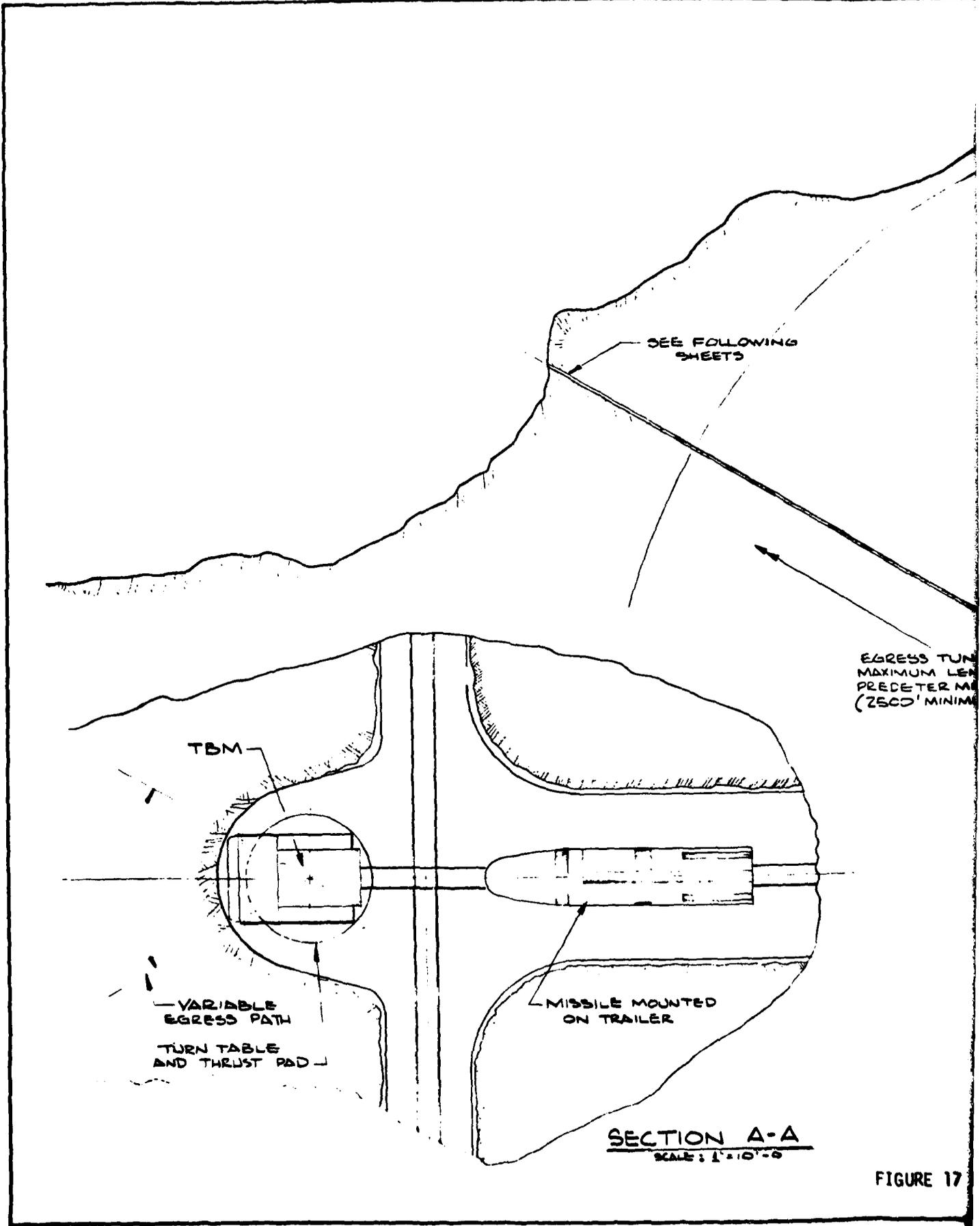


FIGURE 17

REV	DATE	DESCRIPTION	BY	CHKD

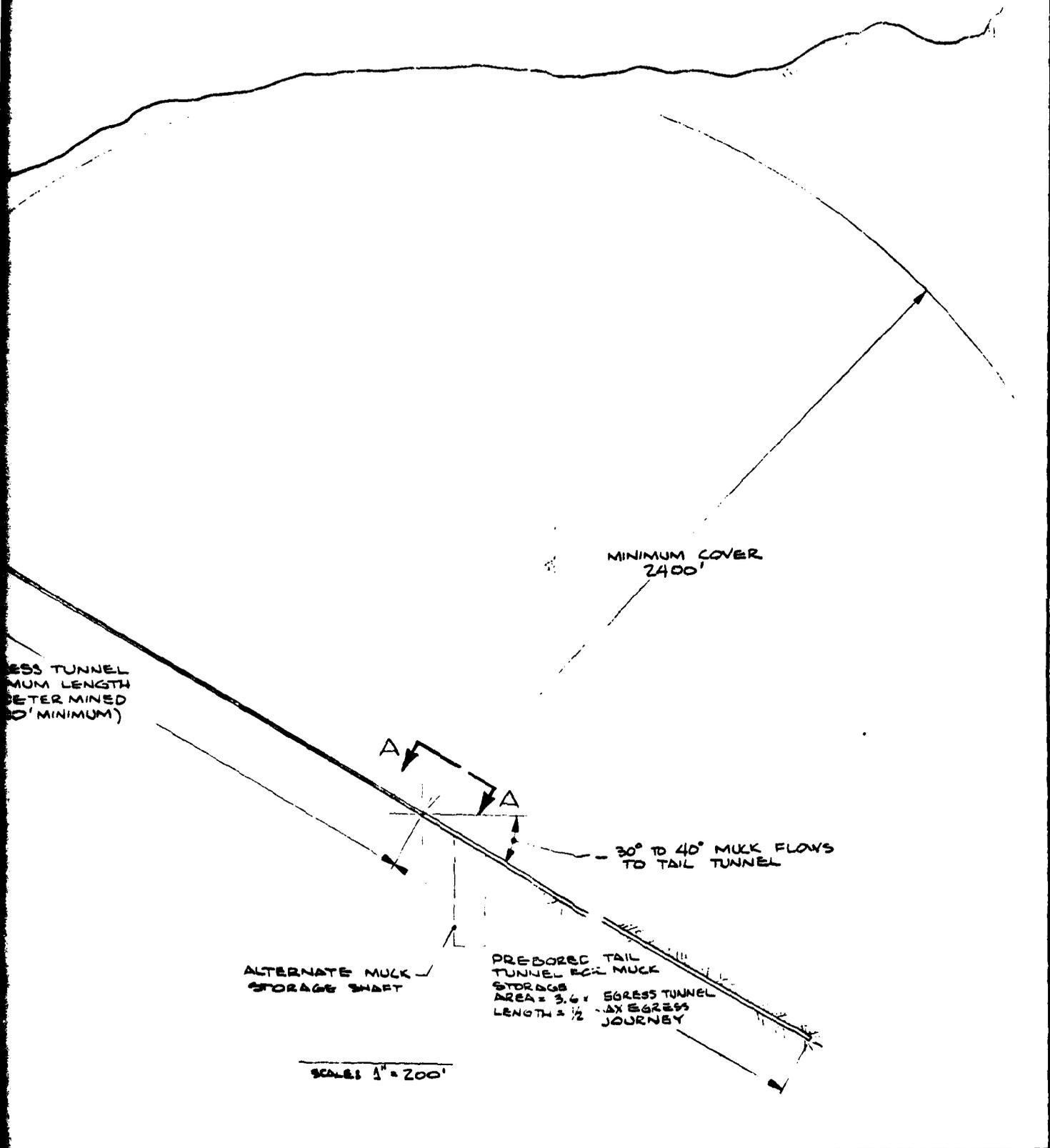
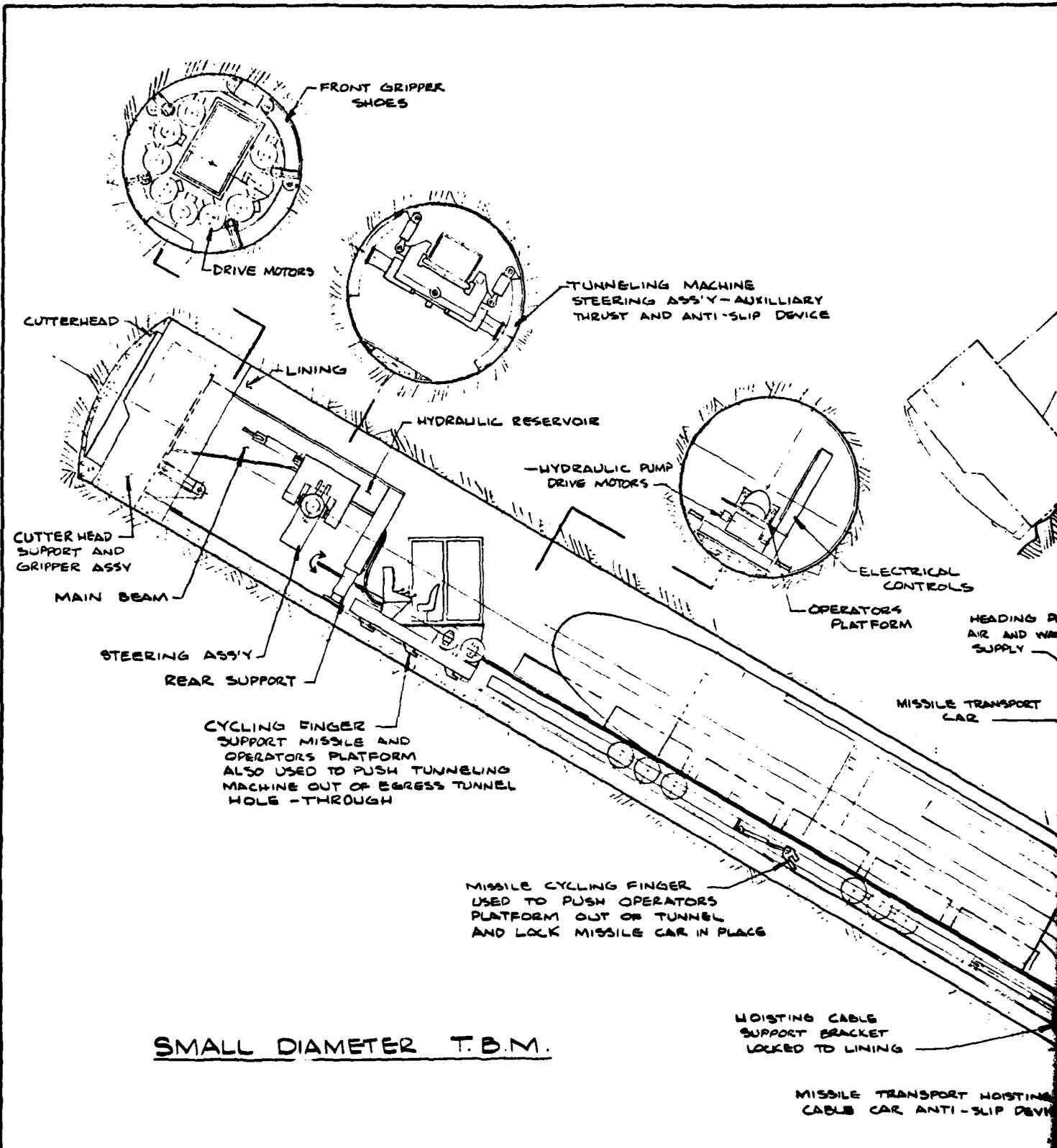


FIGURE 17 - Robbins Egress Layout Concept

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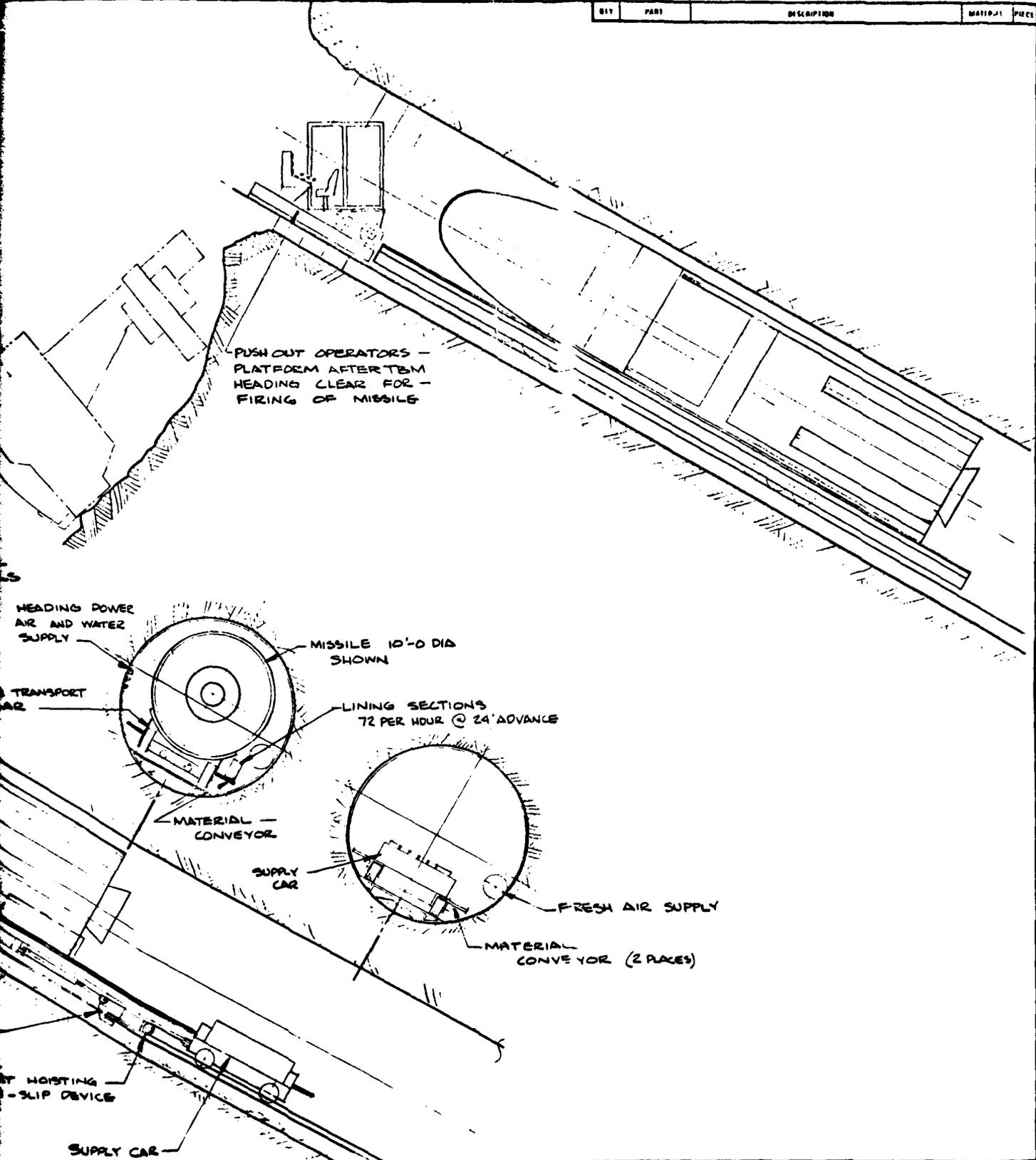
PROJECT	USAF - DEEP BASING PROJECT
NO.	D16450
DATE	JULY 77
SCALE	1" = 200'



SMALL DIAMETER T.B.M.

FIGURE 18 - Robbins Small TBM Missile Operation and Advance Concept

QTY	PART	DESCRIPTION	MATERIAL	PRICE
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TOLERANCES		REV	DATE	DESCRIPTION	BY
FRACTIONAL	ANGLES				
DECIMAL	HOLE				
USAF - DEEP BASING PROJECT					
	DWN	ENGR	DATE 26 JULY 79	D16450	REV 2
	DRAWN	APP'D	SCALE 1/8" = 1'-0"		

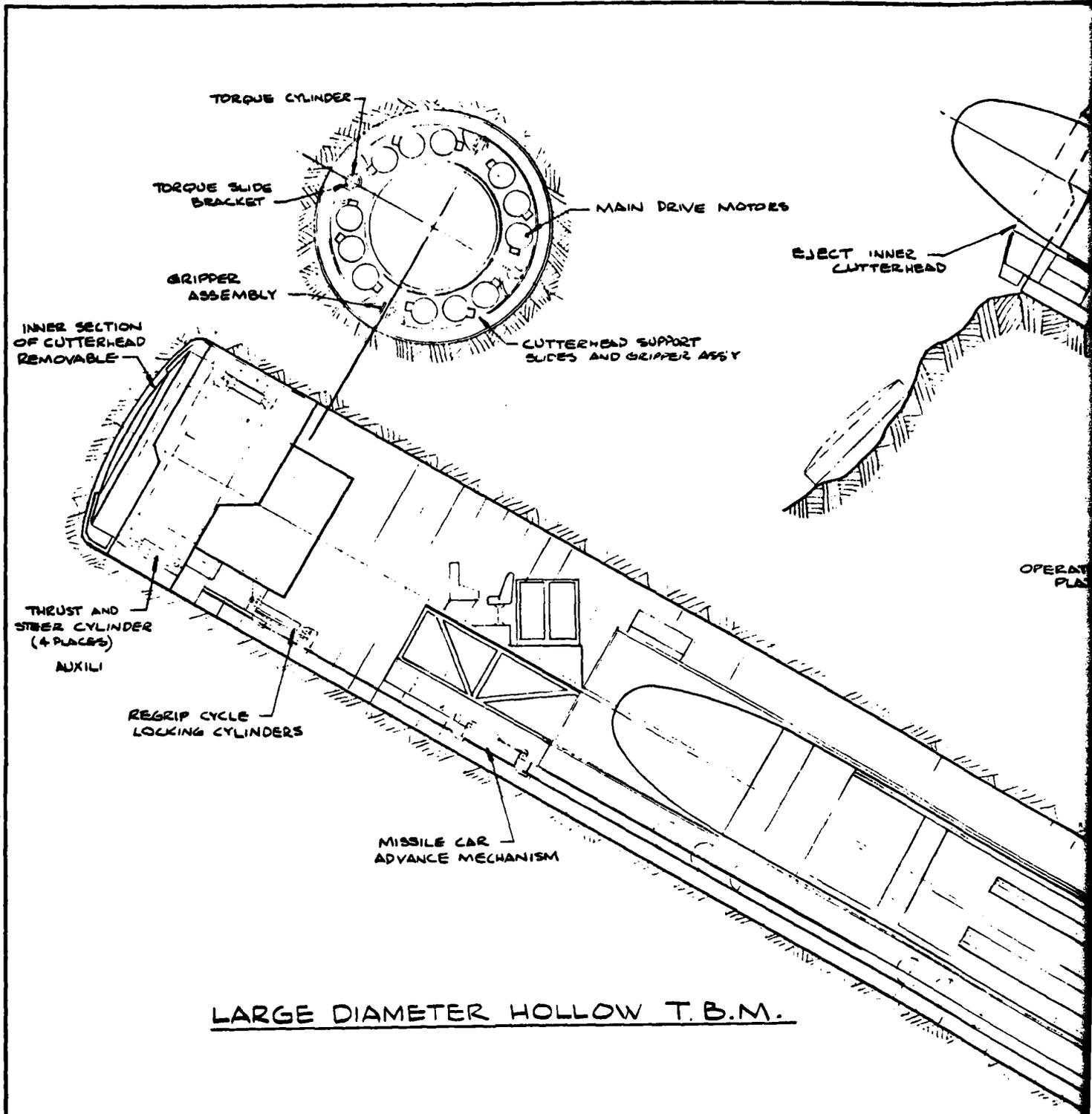
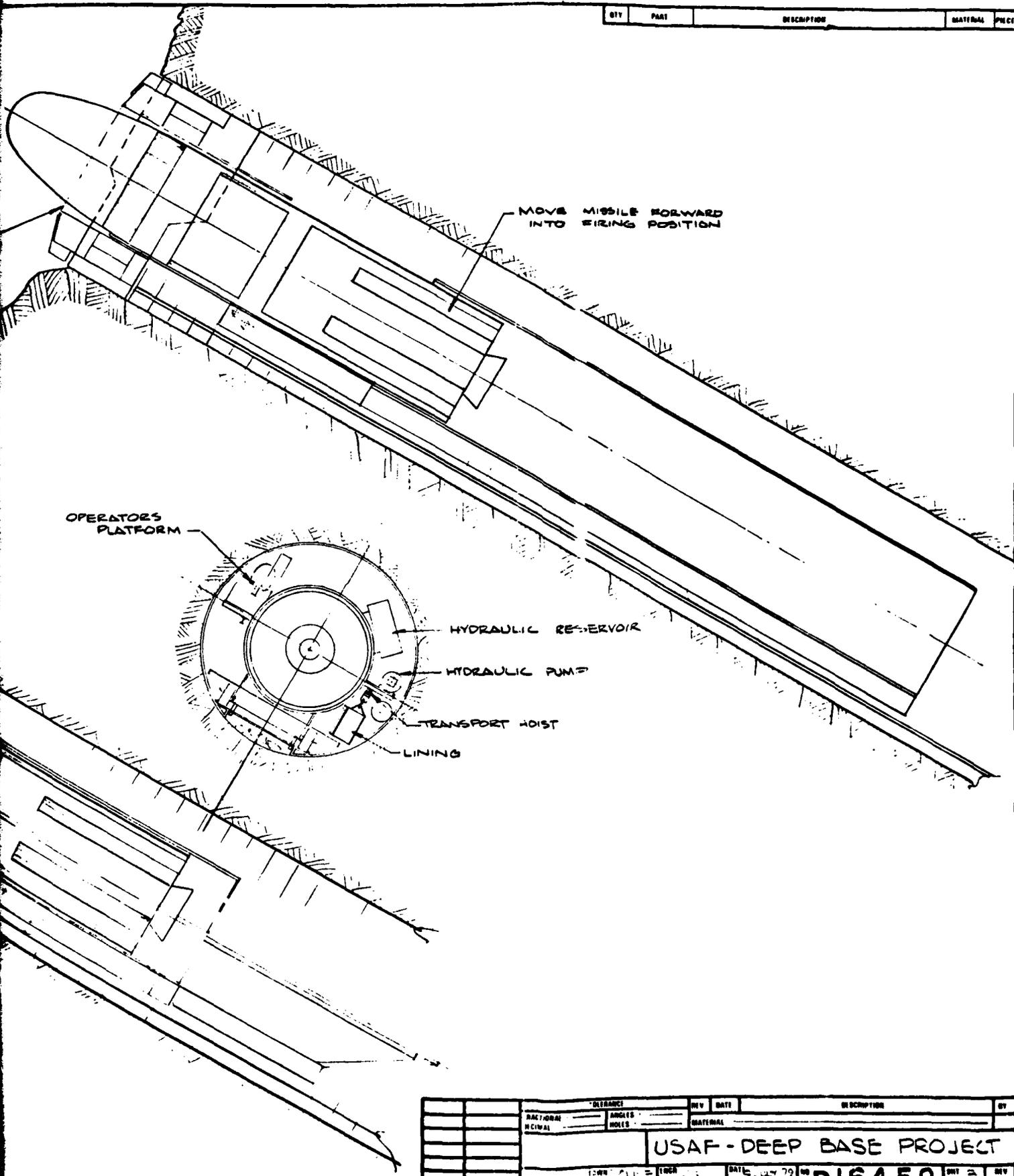


FIGURE 19 - Robbins Large Hollow TBM Concept

QTY	PART	DESCRIPTION	MATERIAL	RECT
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CLEARANCES		REV	DATE	DESCRIPTION	BY
RACTORIAL	ANGLES				
MINIMAL	HOLE				
USAF - DEEP BASE PROJECT					
DATE	SCALE	APP'D	DATE	NO.	REV
JULY 79	1:50			D16450	
DRACON	DE TASSY	WENTERS	1:00		