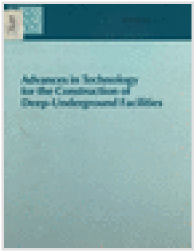

Advances in Technology for the Construction of Deep-Underground Facilities: Report of a Workshop, December 12-14, 1985 (1987)

Pages
65

Size
8.5 x 10

ISBN
0309320852

U.S. National Committee on Tunneling Technology;
U.S. National Committee for Rock Mechanics;
Commission on Engineering and Technical Systems;
National Research Council

Advances in Technology for the Construction of Deep-Underground Facilities

Report of A Workshop
December 12-14, 1985

conducted by the
U.S. National Committee on Tunneling Technology
and the
U.S. National Committee for Rock Mechanics
Commission on Engineering and Technical Systems
National Research Council

Order from
National Technical
Information Service,
Springfield, Va.
22161
Order No.______

NATIONAL ACADEMY PRESS
Washington, D.C. 1987

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The participants in the workshop responsible for this report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Frank Press is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Robert M. White is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of the appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Samuel O. Thier is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Frank Press and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

SPONSOR: This project was sponsored by the Defense Nuclear Agency through U.S. Bureau of Mines contracts J0199025 and J0199030.

Copies of the report are available in limited supply from: The U.S. National Committee on Tunneling Technology, National Research Council, 2101 Constitution Avenue NW, Washington, D.C. 20418.

PREFACE

The workshop, "Advances in Technology for the Construction of Deep-Underground Facilities," was organized at the request of the Defense Nuclear Agency and conducted jointly by the U.S. National Committee on Tunneling Technology and the U.S. National Committee for Rock Mechanics in order to address technological issues important to decisions regarding the feasibility of strategic options. The objectives of the workshop were to establish the current technological capabilities for deep-underground construction, to project those capabilities through the compressed schedule proposed for construction, and to identify promising directions for timely allocation of existing research and development resources.

The earth has been used as a means of protection and safekeeping for many centuries. Recently, the thickness of the earth cover required for this purpose has been extended to the 2,000- to 3,000-ft range in structures contemplated for nuclear-waste disposal, energy storage, and strategic systems. For defensive missile basing, it is now perceived that the magnitude of the threat has increased through better delivery systems, larger payloads, and variable tactics of attack. Thus, depths of 3,000 to 8,000 ft are being considered seriously for such facilities. Moreover, it appears desirable that the facilities be operational (if not totally complete) for defensive purposes within a five-year construction schedule.

Deep excavations such as mines are similar in many respects to near-surface tunnels and caverns for transit, rail, sewer, water, hydroelectric, and highway projects. But the differences that do exist are significant. Major distinctions between shallow and deep construction derive from the stress fields and behavior of earth materials around the openings. At shallow depths, a liner serves as a structural member that is capable of carrying the load of the overburden. As depth increases, a liner must be capable of redistributing the load to the surrounding rock, so that the rock and liner work in concert to provide a stable opening. Also, occurrences of spalling and stress slabbing are unusual in shallow construction but are increasingly prevalent with depth and must be accounted for in the design, excavation, and support processes. Different methodologies are required to accommodate other variations resulting from increased depth, such as elevated temperatures, reduced capability for site exploration, and limited access during project execution. This report addresses these and other questions in chapters devoted to geotechnical characterization, design, construction, and excavation equipment.

Technical capability may be the prime issue affecting the creation of deep-underground facilities, but it is not the only factor that need be considered. A thread that wound through the deliberations for each chapter, and perhaps drew the most attention from the workshop participants, was a nontechnical concern. The success of an endeavor of such magnitude, and one involving a compressed construction schedule and engineering aspects on the cutting edge of technology, was seen to hinge ultimately on the question of contracting and management practices. The proposed project will require concerted interaction by a multidisciplinary team, but the structure of the contract and the attitude and organization of the management team must be flexible to allow such interaction. Current practice in the United States typically does not provide a suitably integrated framework that recognizes the special elements inherent in this type of project.

If the objective of constructing permanent underground facilities on a scale and at a depth that have not been attempted previously is to be achieved, it will be essential to utilize a site with good rock quality, proven rapid excavation methods, crews with a bent toward high productivity, and innovative contracting and management practices. Thus, as the potential threat to defensive facilities increases, it is advisable to establish the capability for construction at the pace and great depths now envisioned. The basic questions are whether it is possible and what technologies must be available in order for deep-underground facilities to be a viable strategic alternative.

U.S. NATIONAL COMMITTEE ON TUNNELING TECHNOLOGY 1985-1986

OFFICERS

DONALD L. VIETH, Department of Energy, Chairman
REUBEN SAMUELS, Thomas Crimmins Contracting Company, Vice Chairman
Z.T. BIENIAWSKI, Pennsylvania State University, Immediate Past Chairman

DESIGNATED REPRESENTATIVES

PHILIP G. MEIKLE, U.S. Bureau of Mines, Federal Agencies
GLEN R. TRAYLOR, Traylor Brothers, Inc., Associated General Contractors
P.E. SPERRY, Tunnel Consultant, American Society of Civil Engineers
JOHN W. WILSON, Advanced Mining and Construction, Inc., American Institute of Mining, Metallurgical, and Petroleum Engineers
LLOYD B. UNDERWOOD, Consultant, Geological Society of America
RONALD E. SMITH, Woodward-Clyde Consultants, Association of Engineering Geologists
J. GAVIN WARNOCK, Acres Consulting Services, Ltd., American Underground-Space Association
HASSELL E. HUNTER, Consultant, Institute of Shaft Drilling Technology

INDUSTRY

JED E. deMERS, Jr., Morrison-Knudsen Company, Inc.
ANDREW F. DEMPSEY, Jr., Dempsey, Bastianelli & Brown
JAMES E. FRIANT, The Robbins Company
VINTON A. GARBESI, Consultant
HARVEY W. PARKER, Shannon and Wilson

GOVERNMENT

CHARLES A. BASKERVILLE, U.S. Geological Survey
ROBERT J. EVANS, U.S. Bureau of Mines
MICHAEL A. GREENBERG, New York City Bureau of Water Supply
JAMES H. MEINHOLZ, Milwaukee Metropolitan Sewerage District
KENNETH D. SCHOEMAN, U.S. Bureau of Reclamation

ACADEMIC AND RESEARCH ORGANIZATIONS

HERBERT H. EINSTEIN, Massachusetts Institute of Technology
ALLEN W. HATHEWAY, University of Missouri at Rolla
THOMAS D. O'ROURKE, Cornell University
LEVENT OZDEMIR, Colorado School of Mines
STANLEY L. PAUL, University of Illinois
RAYMOND L. STERLING, University of Minnesota

Staff

SUSAN V. HEISLER, Director
TERRIE NOBLE, Administrative Assistant

U.S. NATIONAL COMMITTEE FOR ROCK MECHANICS
1985-1986

OFFICERS

HOWARD J. PINCUS, University of Wisconsin--Milwaukee, Chairman and Representative, American Society for Testing and Materials
DOUGLAS D. BOLSTAD, U.S. Bureau of Mines, Vice Chairman
JAMES H. COULSON, Tennessee Valley Authority, Immediate Past Chairman

MEMBERS-AT-LARGE

FRANCOIS E. HEUZE, Lawrence Livermore National Laboratory
THOMAS A. LANG, Consulting Engineer
DON A. LINGER, Defense Nuclear Agency
JAMES E. MONSEES, Metrorail Transit Consultants
WILLIAM G. PARISEAU, University of Utah
CHRISTOPHER M. ST. JOHN, J.F.T. Agapito and Associates
WOLFGANG R. WAWERSIK, Sandia National Laboratories

MEMBER-REPRESENTATIVES OF SOCIETIES

DAVID F. FENSTER, Roy F. Weston, Inc., Association of Engineering Geologists
EARL R. HOSKINS, Texas A&M University, American Geophysical Union
CHARLES H. DOWDING, Northwestern University, American Society of Civil Engineers
SUNDER H. ADVANI, Ohio State University, American Society of Mechanical Engineers
GEORGE A. KIERSCH, Geologic Consultant, Geological Society of America
GARY R. OLHOEFT, U.S. Geological Survey, Society of Exploration Geophysicists
ROBERT G. LUNDQUIST, Ohio State University, Society of Explosives Engineers
VASUDEVAN RAJARAM, Engineers International, Inc., Society of Mining Engineers
H. DONALD OUTMANS, Union Oil Company of California, Society of Petroleum Engineers
C. WILLIAM LOVELL, Purdue University, Transportation Research Board

Staff

LYNNE F. CRAMER , Director
VIRGINIA M. LYMAN, Administrative Assistant

PARTICIPANTS IN THE WORKSHOP

CHAIRMAN

DONALD L. VIETH, U.S. Department of Energy

WORKING GROUP ON GEOTECHNICAL CHARACTERIZATION

DENNIS J. LACHEL, Lachel Hansen & Associates, Inc., Chairman
MICHAEL J. BEUS, U.S. Bureau of Mines
WILSON BLAKE, Consulting Mining Engineer
JAMES H. COULSON, Tennessee Valley Authority
FRANCOIS E. HEUZE, Lawrence Livermore National Laboratory
HOWARD J. PINCUS, University of Wisconsin--Milwaukee
HOWARD R. PRATT, Science Applications International Corp.
MATT S. WALTON*, Minnesota Geological Survey

WORKING GROUP ON DESIGN CONSIDERATIONS

WILLIAM G. PARISEAU, University of Utah, Chairman
Z.T. BIENIAWSKI, Pennsylvania State University
DOUGLAS D. BOLSTAD, U.S. Bureau of Mines
DAVID G. HAMMOND*, Consultant
DANIEL E. HOKENS, U.S. Army Corps of Engineers, Omaha District
THOMAS A. LANG*, Consultant
DOUGAL R. McCREATH, Golder Associates, Inc.

WORKING GROUP ON CONSTRUCTION ISSUES

EDWARD J. CORDING, University of Illinois, Chairman
FRED W. BRACKEBUSH, Hecla Mining Company
THOMAS R. KUESEL, Parsons Brinckerhoff Quade & Douglas, Inc.
JOHN R. MARKS, JR., Homestake Mining Company
JAMES S. REDPATH, J.S. Redpath, Ltd.
REUBEN SAMUELS, Thomas Crimmins Contracting Co.
MICHAEL SOKASKI, U.S. Bureau of Mines
FRANK J. SOLAEGUI, Reynolds Electric & Engineering Co.

WORKING GROUP ON EXCAVATION EQUIPMENT AND SYSTEMS

PRISCILLA P. NELSON, University of Texas at Austin, Chairman
JAMES E. FRIANT, The Robbins Company
TONY J. PEACH, Boretec, Inc.
ELDRED O. MIXON, Kenny Construction Co.
PATRICK D. LINDSEY, U.S. Army Corps of Engineers, Omaha District
RUSSELL J. MILLER, Colorado School of Mines
CARL H. SCHMUCK, Homestake Mining Co.
P.E. SPERRY, Tunnel Consultant

*Unable to attend workshop

CONTENTS

INTRODUCTION AND SUMMARY OF FINDINGS

INTRODUCTION

As one means of determining the feasibility of current and developing concepts for deep strategic facilities, the Defense Nuclear Agency requested that the U.S. National Committee on Tunneling Technology (USNC/TT) and the U.S. National Committee for Rock Mechanics (USNC/RM) organize a workshop to assess advances in technologies and practices related to the construction process. The scope of the workshop was intended to complement a similar activity conducted in 1981 by the U.S. National Committee on Tunneling Technology. The resulting report (1982), Design and Construction of Deep-Underground Basing Facilities for Strategic Missiles, which concentrated on the general technical and management issues raised by the basing option envisioned at that time, served as a significant resource for deliberations at this workshop. Two other documents previously prepared by the committees (USNC/RM, 1981; USNC/TT, 1984) also provided reference material.

The primary difference between the basing concepts considered in the two workshops is the specification of facility depth. The first concepts were proposed at depths that are relatively shallow (2,500 to 3,000 ft) in comparison with current proposals of depths up to 8,000 ft. To address the concept of facilities at the depths now contemplated, the workshop was designed to draw on experience developed in underground civil engineering projects and in the construction and operation of deep mines. The mining perspective contributed valuable insights regarding actual workings at the depths of interest.

U.S. National Committee on Tunneling Technology. 1982. Design and Construction of Deep-Underground Basing Facilities for Strategic Missiles (Volume 1, Evaluation of Technical Issues; Volume 2, Briefings on System Concepts and Requirements). Washington, D.C.: National Academy Press.

U.S. National Committee for Rock Mechanics. 1981. Rock-Mechanics Research Requirements for Resource Recovery, Construction, and Earthquake-Hazard Reduction. Washington, D.C.: National Academy Press.

U.S. National Committee on Tunneling Technology. 1984. Geotechnical Site Investigations for Underground Projects (Volume 1, Overview of Practice and Legal Issues, Evaluation of Cases, Conclusions and Recommendations; Volume 2, Abstracts of Case Histories and Computer-Based Data Management System). Washington, D.C.: National Academy Press.

The participants were selected to represent a variety of expertises as well as practical and theoretical viewpoints. The combination of backgrounds and knowledge--ranging from academicians concerned with basic research to geotechnical engineers to designers and contractors for tunnels and shafts to specialists in mine ventilation--and the resulting mix of opinions were essential in assessing the technologies and practices applicable to the basing concept.

Assumptions

To allow evaluation of technical issues without constraint, the workshop was not restricted to examination of particular systems or schemes for deep-underground facilities. Specifications and requirements were indicated only in broad terms. However, it was necessary to develop some assumptions regarding the geology, extent and lifetime of the facilities, and schedule and means of excavation. Specifically, the assumptions presented to the participants included the following:

- The excavation will consist of a complex network of lined and unlined, short and long shafts, chambers, and tunnels with flat and inclined grades, as well as junctions of various configurations.
- Long-term (50 to 100 years) stability of the openings is essential.
- The construction schedule will be compressed (five years to operable status).
- Excavation will be primarily by mechanical means (i.e., with minimal blasting).
- The range of opening diameter under consideration is 6 ft to 25 ft.
- The range of tunnel length under consideration is from less than 1,000 ft up to 20 miles.
- Depths of construction may reach 8,000 ft.
- Geothermal gradient averages 10°F per 1,000 ft of depth but may be substantially greater.
- Groundwater flows may be encountered.
- Vertical stress increases with depth and horizontal stress varies from less than up to several times the vertical stress.
- The range of rock strength (unconfined compression) includes: soft (less than 10,000 psi), medium (10,000 to 20,000 psi), hard (20,000 to 30,000 psi), and very hard (greater than 30,000 psi).

This set of general assumptions served as the basic framework for discussions at the workshop.

Structure of the Workshop

To focus the workshop, the question of building facilities at great depth was divided into four main components:

- The ability to gather geotechnical information for site selection, design, and construction.
- The ability to specify the configuration of the opening(s) and the nature of the support system.

- The ability to create the opening(s) safely and efficiently.
- The capability of the equipment necessary for mining and rock handling.

To address these areas, four working groups were created. The concepts and basic framework for the working groups were structured in the following manner.

Geotechnical characterization focused on the process of collecting the information necessary to understand the earth's structure and conditions for designing and building the facility, an effort that could require the evaluation of a volume of 15 cubic miles of rock. The outstanding questions centered around the information needed to select a site that has the proper characteristics, a strategy for evaluating an enormous volume of rock in a reasonable time frame, and the technologies required to obtain the information.

Design focused on the processes of specifying the configuration of the facility within the context of the natural rock that must serve as the engineering material. The outstanding questions centered around analysis of the reaction of the rock to the creation of openings, and the specification of the support system necessary to ensure that the openings are stable under the high stresses and time-dependent behavior likely to be encountered.

Construction focused on issues affecting the ability to mine and support the openings in a safe and efficient manner. The outstanding questions centered around the geotechnical conditions that would affect the excavation method and sequence, means to limit risk to health and safety of personnel, and the influence of facility layout on construction performance.

Excavation equipment focused on the tools necessary to support rock breaking, opening stabilization, and muck removal. The major questions centered on current and potential mechanical systems that can perform rapidly and reliably for differing distances and configurations, and constraints on operability that may be amenable to modification in the near term or to application of emerging technologies.

The scope of the working groups was intentionally limited to technical concerns. The political, environmental, and strategic issues surrounding the concept of deep facilities for defensive purposes were explicitly avoided. Other topics deemed inappropriate for specific consideration included nuclear weapons effects, survivability, retaliatory capability, and egress.

FINDINGS FROM THE WORKSHOP

Summaries of the Working Groups

Geotechnical characterization plays a key role in all stages of the development of deep-underground facilities, from initial reconnaissance and site selection through post-construction activities. A phased, observational approach is essential in view of the volume of rock involved and remoteness imposed by its depth, as well as the time constraints of the schedule. Many of the currently available characterization techniques are applicable to the proposed project. However, the ability to evaluate factors that pose special problems for deep-underground projects will require improvements in exploration, testing, and instrumentation technologies. These improvements include development of instruments which work longer under adverse environmental conditions, new technologies for evaluating in-situ stress, and methodology to determine remote fracture systems in 3-D. Equally important is the use of enlightened contracting practices which permit exploration, design, and construction to be integrated into a unified, contemporaneous effort.

Design of stable openings at the depths of interest requires increasing attention to design principles. The technology is not synonymous with the more common, civil construction at relatively shallow depths. Quantitative knowledge of rock mass and support behavior becomes more important, and reliance at least in part on the natural support provided by the rock becomes essential. Interactive design, accompanied by instrumentation and monitoring of the rock/support system, is critical for design validation. Developments that would be beneficial include nonborehole geophysical systems for use at the face, computer programs for analysis of jointed rock-mass and support response under large displacements, and capabilities for integration of yieldable elements into the support system. The design process will demand close ties with geotechnical characterization and construction activities, and the contractual format must be carefully considered to provide for efficient implementation of design.

Construction procedures, performance, and schedule are determined essentially by geotechnical conditions at the site and by layout and design of the facility. Each may impose significant positive or negative consequences that influence construction requirements, efficiency, economy, and safety. Specific concerns that must be addressed in complex operations at depth are temperature and ventilation, in situ stress, groundwater inflow, rock quality, and logistics. Several areas where technological developments can enhance constructibility include boring machine performance in violently spalling ground, efficient installation of support systems with large displacement capabilities, and directional control of raise-drilling pilot holes. A crucial requirement for effective construction will be contracting and management practices that provide flexibility for changes as excavation proceeds.

Excavation equipment and systems currently offer the basic technological capabilities for construction of deep facilities. The geotechnical environment and project layout are important factors in system component selection and function. Full-face boring is the preferred means for efficient tunnel excavation, combined with "no-delay" systems for haulage and support installation. For access shafts, blind boring is potentially the fastest, lowest cost method. For internal shafts, excavation by enlargement of directionally drilled pilot holes is the optimum method. Machine modifications and application of emerging technologies may be expected to contribute substantially to equipment performance.

Contracting and Management Issues

Historically, site characterization, facility design, and project construction have been considered separate and distinct entities. For conventional underground structures, this view has been accentuated in recent years by improved abilities to characterize and evaluate the site, to design openings consistent with the natural conditions, to develop improved materials for construction, and to create stable openings. However, as demands increase for unconventional, deeper structures, the paucity of knowledge and understanding of the site and of the magnitude and degree of variation in rock properties will not allow independence of geotechnical characterization, design, and construction. For a project that challenges technology, it is essential to establish a firm basis for teamwork involving the investigators determining the variations in the site, the designer specifying the fit of the structure to the rock, and the constructors excavating and stabilizing the openings. Consequently, contracting and management philosophies must be oriented to permit, or perhaps demand, adoption of means to ensure close coupling of these activities.

Effective approaches to contracting and management will not only acknowledge the special elements of a project but also provide for equitable sharing of risks, establish clear procedures for timely resolution of design and construction changes as encountered, and foster communications and morale essential to productivity and teamwork (USNC/TT, 1978). In the United States, general practice is to use competitively bid, fixed-price contracts for underground construction. However, a single type of contract cannot suit all circumstances and in some instances is most inappropriate. A prime example of the latter case is a project where the schedule is critical and it is essential to begin construction well before final designs are finished and the plans and specifications completed (USNC/TT, 1974)--a case not unlike the project considered in this report.

In a suitable situation, a fixed-price contract can offer the owner a presumably firm price for the work and motivate the contractor to achieve the lowest possible cost. However, the inherent disadvantages can seriously undermine the ability to obtain a project that is on schedule, within budget (or at reasonable cost), and operates to design. Considerations in the use of fixed-price contracts include the following:

- For competitive bidding, the work must be specified in great detail. Yet, as the work proceeds, the details may be revised to accommodate conditions actually encountered. Thus, a solid basis for preparing a bid rarely exists.
- The contractor is often required to accept extensive risks related to unknown subsurface conditions. The bid reflects this risk in the form of a substantial contingency, and the progress of the work determines whether the contractor or owner benefits. The result is higher initial costs and an adversarial relationship that promotes expensive and time-consuming disputes and litigation.
- Changes during construction--a common occurrence for underground projects--are often expensive and involve readily contested issues of necessity and financial responsibility. When the price for the work is fixed, owners and contractors are forced to adopt rigid, defensive positions that not only can affect construction performance but also lead to costly schedule delays, disputes, and litigation.
- Inflexibility in contracting discourages the use of innovative design and construction techniques and improved technologies, thereby resulting in unnecessarily high costs for construction.

U.S. National Committee on Tunneling Technology (1978). Better Management of Major Underground Construction Projects. Washington, D.C.: National Academy Press.

U.S. National Committee on Tunneling Technology (1974). Better Contracting for Underground Construction. Washington, D.C.: National Academy Press.

A suitable contracting and management framework will acknowledge the special elements of the proposed project and the constraints imposed by great depth, long tunnel lengths, and compressed schedule. Neither time nor resources will permit securing preconstruction geotechnical information sufficient to define the work for fixed-price bidding. In general, maximum economy and minimum disputes will result if the contract documents include risk-sharing provisions, anticipate and provide means for resolving the types of construction problems that may be encountered, and permit contractor compensation in the manner that costs are incurred. Such a system is commonly used overseas, although it is relatively novel for U.S. projects. In Canada, however, a similar system was used successfully for the Rogers Pass tunnel, where the constraints resemble the proposed project. Another means to minimize bid contingencies and disputes and delays during construction is appointment of a Disputes Review Board prior to construction. Such boards have been successfully engaged for the Eisenhower and Mt. Baker Ridge tunnels in the United States.

Conclusion

The consensus of the working groups is that the basic technical capabilities to create complex underground facilities at the pace and depths envisioned are available in current practice. The necessary improvements and advances in technology hold reasonable potential for development within a short to moderate period of time. Therefore, efforts to initiate a deep-underground facility could be undertaken while the technical developments are being pursued. For major civil projects, a confident approach often signals the demand that naturally attracts technological achievements.

The consensus also is that the issues and limitations to be resolved are varied, often intricate, and sometimes formidable. Although the technical basis continues to expand, the practice of designing and constructing an underground facility is still less a science than an art. The accent on art lies in assembling components of exact specifications and known response into a set configuration within a basic engineering material for which neither the characteristics nor behavior can be determined with precision. The concept of extensive, deep-underground facilities tests the farthest reaches of technology and art, as well as the mettle of the parties involved throughout the design and construction processes. However, the path from concept to completion does not appear to present insurmountable obstacles.

The challenges in creating deep-underground facilities are not solely technical in nature. An integral part of the endeavor, and an issue that is fundamental to success, is the philosophy practiced in contracting and managing the project. The structure of the contract and the organization of the management team will have to be both flexible and highly integrated. Each will have to be implemented in a manner that recognizes the essential interdependence of geotechnical characterization, design, and construction.

GEOTECHNICAL CHARACTERIZATION

Geotechnical characterization for deep-underground facilities (i.e., depths of 3,000 to 8,000 ft) constitutes a mix of old, new, and emerging technologies. Most of the currently available characterization techniques are applicable to the data requirements of the proposed program. However, there is a need to improve certain technologies and a critical requirement to identify specific features as early in the exploration program as possible. The volume of rock is enormous and remote, the potential for conditions particularly adverse to design and construction is significant, and the schedule for the project is compressed.

These considerations cannot be accommodated properly within the structure commonly adopted for a geotechnical program. Typically, the exploration phase is completed prior to design and detailed characterization is completed prior to construction. For a deep-underground facility, this approach is not a prerequisite of initiating either design or construction.

The recommended geotechnical program includes the use of an iterative approach that analyzes the exploration data as they are produced and prior to implementing the next step in exploration. In this manner, "fatal flaws" are identified early and a site abandoned before any additional funds are used for characterization. Further, this iterative approach is also intended to be interactive: explorations are conducted in cooperation with the designers and constructors and continue through the design and construction processes.

The iterative/interactive approach assumes a multidisciplinary team of engineers, geologists, and contractors experienced in deep-underground projects. This geotechnical design team should be supplemented by an independent peer review group which meets on a regularly scheduled basis from project inception through completion of construction. Geotechnical characterization must be an integral part of the entire project.

Many of the philosophical concerns applicable to a geotechnical program for deep-underground construction are presented in a recent case-history study of underground projects (USNC/TT, 1984). That study also addresses some of the supportive contracting and management philosophies that permit the exploration effort to contribute effectively to all project phases.

U.S. National Committee on Tunneling Technology. 1984. Geotechnical Site Investigations for Underground Projects. Washington, D.C.: National Academy Press.

ELEMENTS OF CHARACTERIZATION

The program of exploration is intended to generate geotechnical data from the initial reconnaissance through post-construction phases of the project. The effort to characterize a site requires the continuous development and analysis of information on a variety of factors which, either separately or in differing combinations, may affect several aspects of the project. Thus, it is essential that detailed exploration continue concurrently with design and construction.

Facilities at the depths envisioned involve a significant potential to encounter elevated ground temperatures, adverse lithology and structure, high in-situ stresses, and high-pressure inflows of water. Another concern, ground shock attenuation, is critical to strategic facilities at these depths. These factors are considered most important because substantial occurrences could preclude reasonable construction or operation. For example, extensive shear zones, very soft rock, and excessive stresses would prevent safe construction.

The elements of characterization and their applicability to design, construction, excavation equipment, and static and dynamic loading are indicated in the matrix shown as Table 1. The significant elements for each category are noted by an "X" in the appropriate column. Sequence or other time-dependence is not implied by relative position in the matrix. For example, temperature data may be used for design purposes before, during, or after the same or other temperature data are used for some phase of construction.

Each of the "Critical Geotechnical Parameters" is considered to be critical because of the potential to establish a "fatal flaw": that is, a single parameter may be sufficiently unfavorable for design, construction, or performance to disqualify a candidate site. Under some circumstances, a factor such as very low unconfined strength may serve the same purpose.

"Design" clearly relies extensively on the range of characterization elements. As might be expected, the close relationship between "Construction" and "Equipment" is reflected by a similarity in applicable elements. The remaining columns call attention to the characterization parameters required to address the ability of the host rock to support and transfer loads.

Influence of Characterization

The influence of characterization on individual aspects of a project is extended by the interaction between these aspects. For example, Table 2 summarizes the manner in which geotechnical elements and facility layout affect equipment for excavation and support installation. In this case, characterization is significant not only directly but also indirectly via the relationship between facility layout and equipment.

Geotechnical parameters are of central importance in system component selection and function. For example, a full-face tunnel boring machine (TBM) designed for optimum performance in soft rock is not capable of efficiently cutting hard rock unless modified (e.g., larger diameter cutters, increased hydraulic-thrust pressure) The potential for encountering substantive changes in rock conditions must be anticipated so that the machine design can incorporate the specific features that allow such modifications. A particular concern overall is the possible presence of poor-quality rock of sufficient extent to interfere with mining, as well as excessive water inflows and gas.

Equally important to equipment selection is the project layout, which is itself subject to the characterization process. The geotechnical environment

TABLE 1 Elements of Characterization for Deep-Underground Projects

	Design	Construction	Equipment	Static Loading	Dynamic Loading
CRITICAL GEOTECHNICAL PARAMETERS					
Temperature (rock mass)	X	X	X		
Shock attenuation (rock mass)	X				X
Structure (including discontinuities)	X	X	X	X	X
Stratigraphy	X	X	X	X	
In-situ stress	X	X	X	X	X
Hydrology	X	X	X	X	X
Other liquids and gas	X	X	X		
PHYSICAL PROPERTIES/BEHAVIOR					
Hardness		X	X		
Density	X			X	
Porosity					X
Permeability (rock mass and intact rock)	X	X			X
Modulus/deformability	X				
Elastic wave velocity	X				X
Strength					
unconfined	X	X	X		
confined	X				
loading (repeated)	X				X
Controlled strain path	X				
Resistivity (electric)	X				
Thermal conductivity*	X				
Heat capacity	X				
Creep	X	X			
Squeezing index	X	X	X		
Plasticity indices	X	X	X		
Chemical reactions	X	X	X		
Petrography		X	X		

*Also thermal diffusivity.

is a critical factor in determining the stability of openings and the appropriate configuration for tunnels, caverns, and shafts. In like manner, the geotechnical environment must be carefully considered in the plans for inclines and declines, which may present requirements vastly different than tunnels or caverns. All of these layouts influence selection of equipment, which may in turn restrict grades and turning radii. The interactive nature of design and construction is clearly exemplified here.

TABLE 2 Influence of Characterization and Layout on Selection of Equipment for Excavation and Primary Support

	Geotechnical Elements				Layout			
	Intact Rock Strength	Rock Mass Condition	Over-stress Failure	Water	Depth	Decline*	Incline*	Curves
Boring Equipment	M	M	I	m	m	m	M	m
Cutting Tools	M	I	0	m	0	I	0	M
Muck Transport								
At heading	m	m	0	M	0	M	m	m
Horizontal haulage	m	m	0	M	0	M	m	M
Vertical haulage	m	M	0	M	M	M	M	M
Primary Support	m	M	M	M	M	m	m	m

*Assumed greater than 15 percent.

Legend: M (major) = strong impact on system component selection and function.
I (intermediate) = significant impact but not an overriding influence.
m (minor) = some consideration should be given for equipment selection.
0 (no influence) = little impact on equipment selection.

PHASED APPROACH TO GEOTECHNICAL CHARACTERIZATION

The magnitude of the proposed project and the compressed schedule dictate that special care be taken to integrate exploration, design, and construction into a unified, contemporaneous effort. The volume of rock involved and remoteness imposed by its depth, as well as time constraints, eliminate the possibility of obtaining data sufficient to provide suitable knowledge of the underground prior to construction. Therefore, a phased observational approach is essential. This approach to the geotechnical effort will allow identification of a location with enough certainty to initiate the project, while the details required for final design and effective construction are determined according to information obtained at depth as construction proceeds.

It is assumed that an initial screening process to identify approximately 25 potential sites, each about 10 square miles in plan, will precede the program for geotechnical characterization. The program would then involve four broad phases: site selection, site characterization, construction, and post-construction.

Phase I Site Selection

Preliminary site selection is intended to reduce the number of possible sites from approximately 25 to 3 candidates that are geotechnically most promising. At this stage, lack of physical access to the 25 sites is an imposed constraint. Therefore, all available sources of existing information must be carefully examined--e.g., mines, boreholes and logs, geologic and topographic mapping, state and federal geologic survey data, oil and gas drilling data. These sources should be supplemented, if necessary, by techniques such as remote sensing with systematic analysis. The critical factors to evaluate include lithology, geologic structure, temperature gradient, in-situ stress, shock attenuation characteristics, hydrology, and existence of hazardous gas. The systematic evaluation of potential sites will allow the selection of three candidate sites, as well as the proposed depth of installation for each site and the possible locations for access openings.

The next stage in the site selection process involves field exploration efforts at each of the three candidate sites. Field work should progress immediately with detailed surface mapping, hydrologic studies, and one hole drilled to at least 500 ft below the proposed maximum depth of installation at each site. Complete suites of tests on the core and in the holes should be performed to establish values for all pertinent design and construction parameters. Additional boreholes should be planned carefully, with the spacing and location of each hole chosen to satisfy individual conditions at each site. It is anticipated that a minimum of 5 holes per 10 square miles of surface area will be required during the selection process. The testing program should also include experiments designed to estimate characteristics of shock attenuation. Both mathematical simulation and field testing with high explosives should be considered for this purpose.

A detailed geotechnical report of the three candidate sites should be prepared. This report, coupled with preliminary design, construction, and operation schemes, will allow selection of a single site for construction.

Phase II Site Characterization

Initially, detailed site characterization should be accomplished primarily with exploration shafts and tunnels. It is important that these shafts and tunnels be located to maximize geotechnical results while providing access to all critical depths of construction. Tunnel lengths from 5 to 10 percent of the final design length within each distinctive geological unit should be appropriate for exploration purposes. A complete suite of in-situ testing should be performed to establish values for all pertinent design and construction parameters.

The characterization program should also include development of adequate methods for mapping geology, water conditions, gas seepage, and drillability ahead of advancing tunnel faces, and for monitoring the overall performance of completed tunnels, shafts, and linings. Techniques and instrumentation for use in the tunnel should be designed for application during tunneling without impeding operations, rather than just during downtime of equipment. However, this capability will require development of new technology and specialized hardware.

A comprehensive geotechnical report that is both factual and interpretive, carefully distinguishing between each, should be prepared at the end of this phase. This report will provide the basis for construction bidding and final detailed design.

Phase III Construction

It is expected that construction will proceed on a cost-plus or cost-reimbursement basis, because preconstruction information will be insufficient to define the work suitably for fixed-price bidding. The geotechnical team should utilize advance drilling, remote sensing, and post-construction monitoring to validate predictions of face conditions and to project possible trouble areas. The team should also establish the pay schedule according to conditions actually encountered during construction.

Exploration must be a continuous and integral part of the construction process. As information and data are developed, the results should be used to modify construction techniques and the design, as appropriate. The exploration program should be designed, however, to minimize its impact on the construction schedule. For example, monitoring instruments could be installed during maintenance periods to to prevent interference with mining progress. Further, every opportunity must be pursued to continue development of remote techniques to predict groundwater conditions, locations of critical discontinuities, and changes in drillability ahead of the advancing tunnel.

Phase III of the program should be completed with a comprehensive report of as-built conditions. The report should include the construction history, detailed geologic mapping, areas vulnerable to problems in the future, and any geotechnical concerns bearing on responsiveness to hostile circumstances.

Phase IV Post Construction

Geotechnical responsibilities will continue for the service life of the project. During routine operations, monitoring of convergence/stress, water inflow, gas inflow, seismicity, support systems, and chemical and physical deterioration of geotechnical components will be required. In addition, any anomalies encountered during construction should be observed for possible effects. The information garnered during operations will provide feedback useful to projects anticipated or under way at additional sites.

In the event of hostilities, geotechnical knowledge will be vital to the continuing operation of the installation. Geotechnical skills and data will be necessary to assist in determining point of impact and ground shock intensity, changes in hydrology, stress, and temperatures, and in evaluating drainage. Here, archival information and experienced personnel regarding the underground environment will be invaluable to strategic and tactical planning.

CHARACTERIZATION TECHNIQUES FOR 3,000- TO 8,000-FT DEPTHS

In general, characterization techniques and instrumentation that are suitable for shallow depths (less than 3,000 ft) can be applied satisfactorily at greater depths. The rock mass and support response can be projected to the greater depths and the appropriate modifications incorporated into the techniques and instrumentation. However, several key environmental factors may be introduced that are unique to deep-underground projects. These factors include the potential for (a) corrosive waters, (b) very high operating temperatures and, for strategic facilities (c) high shock loads and (d) high electromagnetic pulse (EMP) loading. The ability to evaluate these factors will require specialized tests, techniques, and instrumentation.

Testing and instrumentation programs during the geotechnical exploration, construction, and operation phases of the project will require extensive use of boreholes. Determination of the location and number of boreholes for characterization can be aided by the use of decision analysis techniques. Statistical correlations and analyses of borehole data, such as with the Kriging method, will improve geologic extrapolations between boreholes and help identify the best locations for additional borings.

Testing and Measurement Techniques

DYNAMIC

Dynamic tests should be conducted to obtain rock mass properties and to assess behavior characteristics such as ground shock attenuation and block motion under dynamic loads. These determinations should also be used to evaluate various types of structural linings. Appropriate dynamic techniques include the following:

- specialized geophysical logging to obtain dynamic elastic moduli (3-D velocity) and seisviewer logs to obtain fracture orientation.
- specialized geophysical surveys both in vertical holes from the surface and in horizontal holes at depth (e.g., vertical seismic profiling [VSP], tube wave velocity surveys, and cross hole surveys).
- high explosive tests at surface, with appropriate instrumentation over a range of depths to measure stress, velocity, acceleration, displacement, and attenuation.
- high explosive tests at depth to measure rock mass properties, attenuation, block motion, and dynamic joint properties.
- high explosive tests at depth to measure response of in-place structures to a shock environment.

HYDROLOGIC

Hydrologic tests are required to measure characteristics of groundwater flow and to evaluate flow characteristics of fracture systems. Fracture systems have been found to play the dominant role in control of groundwater inflows in crystalline rock and in highly fractured rock masses. The types of tests will vary, depending on the effective porosity and permeability of the rock matrix and the intrinsic fracture/jointing system. Pressure and injection tests should be used to obtain hydraulic conductivity and storage coefficients of fracture zones. Formational-pump, constant-head, and slug tests can be used for zones of high permeability. Transient-pulse or slug withdrawal tests should be used for the tighter formations, or zones with little fracturing/ jointing.

THERMAL

Thermal measurements of the rock and fluids in the rock are required for environmental monitoring and to assist in establishing the range in which temperature-dependent rock properties are to be determined. Thermal conductivity, heat capacity, and the coefficient of thermal expansion are required for rock at and near excavation surfaces and for each of the distinctive types of earth materials between the ground surface and the underground excavations. Measurements should also be obtained from boreholes drilled for other tests. The design of the measurement program should assume anisotropy unless and until accumulated measurements indicate otherwise.

IN-SITU STRESS

Traditional techniques for measuring in-situ stress cannot be used for stress determinations in deep boreholes. Hydrofracturing is the only direct measurement technique currently available that is applicable under such conditions. Stress data from hydrofracturing should be supplemented by other indirect stress determination techniques using oriented cores, such as differential strain curve analysis (DSCA) and anelastic strain recovery (ASR). Borehole observations of sidewall elongation or spalling and wellbore breakout also can be used to determine the orientation of the horizontal stresses. In a vertical borehole, core discing is an indication of high in-situ horizontal stress.

LIMITATIONS TO TESTING AND MEASUREMENT TECHNIQUES

The greatest obstacle to testing and measurement is presented by the extent of the rock mass that is subject to evaluation. For strategic facilities, suitable means to assess attenuation is an additional concern. To address the major limitations of current testing and measurement techniques, it is necessary to:

- develop dynamic in-situ tests to characterize the rock mass over tens of meters.
- design a dynamic test to obtain attenuation properties of a rock mass volume at the stress levels of interest.
- improve current methodology and techniques to determine (a) a 3-D fracture system within the rock mass away from the borehole/tunnel, and (b) the hydrologic, thermal, and thermomechanical characteristics of large volumes of rock.

Instrumentation and Monitoring Techniques

DYNAMIC

The capability to assess the dynamics of the rock system is of primary importance to the long-term structural integrity of the facility. For strategic purposes, monitoring is essential to address degradation of the rock mass because extensive degradation may not allow it to function as a viable structure following hostilities. An instrumentation and monitoring scheme should encompass the rock mass, the support system, and ancillary facilities. Devices that may be incorporated into this scheme include velocity gages, stress gages, accelerometers, and large block displacement or shear strips.

HYDROLOGIC

Changes in the hydrological regime are a prime concern during construction, normal operation, and following hostilities. Inflow exceeding handling and disposal capabilities could readily lead to problems ranging from difficult to catastrophic. It is doubtful that gravity drainage will be possible at a depth of 8,000 ft. Therefore, flow meters should be installed and pumping water monitored for careful control of the hydrological regime. Sealed piezometers should be installed in boreholes within the facility, particularly at critical locations (e.g., power plant, command and control centers). Active dewatering throughout the service life of the structure is necessary, regardless of natural drainage conditions. This will enhance shock absorption capabilities of the facility. In addition, continued pumping will enlarge the "cone of depression," thus aiding in both temperature and water control, particularly if an aquifer is magmatic in origin as opposed to surface recharge.

THERMAL

Temperatures of the rock and the fluids in the rock should be monitored at the surface of the underground excavations and in boreholes extending from the excavation surface to depths of up to several diameters of the excavation. In addition, temperatures should be monitored from the ground surface down to the excavations in vertical intervals sufficiently small to characterize each distinctive vertical temperature gradient.

STRESS/STRAIN

Stress/strain changes in the rock mass and support system are important parameters, both throughout the life of the structure and during and after hostilities. Rock mass response to loading may be deduced from changes in support stress. Several techniques are readily available to obtain support and rock mass measurements. Suitable instrumentation includes pressure cells and embedded strain gages in the liner or backpacking systems, strain gages in steel liners, sets or bolts, and rock mass stress change devices installed in boreholes.

DISPLACEMENT

Displacement of the rock mass is a very reliable parameter for assessing long-term performance of the structure and response to extraneous loading. Devices to measure displacement are perhaps the most developed of any geotechnical measurement systems and are the most straightforward in terms of data analysis and interpretation. Multi-station extensometer arrays should form an integral part of the facility monitoring system, both during and after construction. A 5- to 10-year operating life is reasonable for displacement monitoring systems in adverse environments.

CHEMICAL

The chemical regime, both initial water and rock chemistry, should be monitored closely. Attention should be devoted to alteration in the regime, especially as might apply to support systems (e.g., steel, grout). The approach may consist of something as simple as pH monitoring of facility discharge or monitoring of particular chemical constituents such as chlorites, sulfates, and carbonates. Specific concerns would be the possible effects of long-term seepage which may be corrosive or the presence of water in conjunction with stray electrical current.

LIMITATIONS TO INSTRUMENTATION AND MONITORING TECHNIQUES

The major overall limitation of instrumentation and monitoring schemes is instrument performance over both the short and long term--a direct function of the facility environment. For the long term, the limitation would encompass all devices to some extent, but particularly electronics subject to hot, corrosive water and perhaps to EMP. Other constraints are that stress change measurement in boreholes is marginally successful and that dynamic stress changes are poorly understood. Data transmission over long distances is just now being perfected with multiplexed digital transmission over fiber optic cable. In-shaft data acquisition might be particularly difficult due to the effects of falling debris on the instrumentation.

SUMMARY

Geotechnical characterization plays a key role in all stages of the development of deep-underground facilities, from initial reconnaissance and site selection through post-construction. A well-developed, iterative, systematic approach to explorations and review, combined with the use of qualified personnel, provides the basis for design and, more importantly, identifies factors which could make the project unsafe or impractical to build and/or maintain.

The principal focus of geotechnical investigations should be on in-situ testing during construction of primary openings and follow-up validation of structure performance in a rock mechanics test bay. This approach will yield a much larger data base on design factors related to construction than can be achieved by ground-surface based measurements. In-situ testing integrates the effect of rock mass discontinuities into measured response. Quantifying the scale effects is not critical for construction but can result in lower costs, improved safety, and increased chances for a successful project.

Although many of the currently available techniques are applicable to the proposed program, improvements in site characterization technology are needed for the depths envisioned. These improvements include development of instruments which work longer under adverse environmental conditions, new techniques for evaluating in-situ stress and shock attenuation, and methodology to determine remote fracture systems in 3-D. Equally important is the use of enlightened contracting practices which permit the investigators, designers, and contractors to work together to solve the geologically based problems as they occur.

DESIGN CONSIDERATIONS

This working group was responsible for assessing the design technology for stable underground openings at depths greater than 3,000 ft, and possibly as deep as 8,000 ft. Deliberations focused on the overall design process and the major features of design pertaining to opening stability. Throughout, design was viewed as an iterative and interactive process that requires close ties with geotechnical characterization and construction activities.

It is expected that preconstruction geotechnical investigations will be limited inevitably because of the depths envisioned for the proposed project. Consequently, the initial design approach must be based on generic or assumed typical conditions. The requirements of this approach include:

- characterization of the typical classes or types of potential ground failure conditions anticipated throughout the site.
- description of typical rock reinforcement or support for each type of anticipated failure mechanism.
- estimation of the quantities of each typical support section likely to be encountered along the project route.
- determination, during construction, of typical support or reinforcement (including no support) that is most appropriate for the actual ground conditions encountered.
- monitoring of the response of the ground and support systems, leading to validation or modification of the initial approach.

Efficient implementation of the design will require careful consideration of the contractual format under which the construction takes place. Attention should be directed towards the recommendations contained in a previous study of contracting practices (USNC/TT, 1974), as well as to the system currently being used for the Rogers Pass tunnel project in Canada. For that project--where similar constraints apply as for the project considered here--the contract documents anticipate the types of construction problems, provide means for resolution, and permit contractor compensation in the manner that costs are incurred.

U.S. National Committee on Tunneling Technology. 1974. Better Contracting for Underground Construction. Washington, D.C.: National Academy Press.

DESIGN PROCESS

The design process is a sequence of activities undertaken with the objective of insuring stable underground openings for the life of the structure. Preconstruction design will be based on generic or typical conditions. Subsequently, the initial assumptions will be reviewed and refined during construction as site characterization data are developed. The process design is the same for both the preconstruction and construction phases, but the level of detail is significantly different.

The design process begins with an examination of site characterization data with an eye for potential failure mechanisms over the proposed layout. The type of failure mechanism is the basis for selecting the analytic technique appropriate for estimating the rock response to loads during and after construction and, ultimately, selecting the type of support for the structure. The analytic technique dictates the type of data input needed to arrive at support requirements. Instrumenting areas both during and after construction provides an objective means of validating and, if necessary, modifying the initial design analyses and support recommendations. The type of information required from instrumented areas depends on the analytic technique.

Table 1 summarizes the design process, listing the common failure mechanisms encountered in underground construction with the appropriate methods of analysis and the data input requirements for the analysis. Typical support methods for the various failure mechanisms are noted by cross reference to Table 2.

TABLE 1 Major Features of the Design Process

Failure Mechanism	Method(s) of Analysis	Data Input	Typical Support Systems*
Structural	Kinematics Empirical	(a)	1, 2, 3
Strength/stress	Stress analysis/failure criteria/failure mode Empirical/experience	(b)	2, 3, 4, 6
Fault/shear zone	Empirical	(c)	4, 5, 6
Time-dependent	Stress analysis	(d)	4, 5, 6

*The numbers correspond to the types of support listed in Table 2.
(a) unconfined compressive strength or appropriate material behavior model; spacing, orientation, condition (persistence, separation, roughness, weathering, filling) of joints; groundwater flow and pressure.
(b) deformation moduli, intact strength properties, rate dependent properties (dynamic/creep), joint properties, anisotropy, in-situ stresses.
(c) nature and distribution of faults.
(d) creep/relaxation moduli, "aging" of material properties, dynamic.

Failure Mechanisms

Four failure mechanisms are identified in Table 1: structural, strength/stress, fault/shear zone, and time-dependent (squeezing/swelling/ creep). "Structural" refers to failures that are of kinematic origin precipitated by an adverse combination of joint and opening geometry. "Strength/stress" refers to the situation where in-situ stress exceeds the rock strength in such a manner as to pose a threat to an opening. The progression of local failure to threatening proportions may involve brittle fracture and strain softening or flow in a ductile manner. Both modes are possible but have different consequences for support loading. "Fault/shear zone" refers to a failure mechanism activated when a heading enters an unsuspected fault zone possibly containing a large volume of water, sand, or clay. "Time-dependent" refers to failures that may result from (1) degradation of material properties as a consequence of diffusion processes collectively known as "aging," (2) a viscous component of deformation, creep, or plasticity, and (3) dynamic overstressing.

Analytic Methods

Structurally controlled failures may be anticipated by an analysis of the joint block kinematics in a systematic way using limiting equilibrium analysis (key block theory) or by empirical correlation with rock mass classification schemes.

Stress controlled failures require calculation of the displacement, strain, and stress changes about an opening as it is excavated. The complexities of the problem likely will require the use of computer-based techniques such as the finite element, distinct element, and boundary element methods. The stress changes, when added to the pre-excavation stresses, allow for a comparison with strength, if done purely elastically. If done elastic-plastically, an estimate of the extent of progressive yielding is possible. The extent of the yield zone (if any) as excavation proceeds is an important design aid.

Fault zone failures lack consistency in either their geometry or the nature of the materials involved. Such failures are best handled empirically as encountered, because each occurrence usually presents unique characteristics.

Time-dependent failures require an analysis of stress that includes time-dependency in the constitutive equations (stress-strain relations) in the form of time-dependent material properties or viscous deformation. Dynamic or transient loading usually implies inertial forces and wave effects. However, a quasistatic loading analysis may be adequate, depending on the nature of the transient.

The excavation sequence followed during construction may lead to stress concentrations significantly different from those associated with the final excavated geometry. For example, a tunnel/tunnel intersection, if formed by advancing one tunnel towards the other, creates a situation where the advance is towards a zone of high stress concentration on the rock being mined as well as on the rock that remains after completion of the structure. A preferable sequence would involve advance away from zones of high stress concentration. For this reason, stress analyses that account for the excavation sequence are needed in order to quantify stress changes induced during construction as well as those associated with the final, fully excavated geometry.

Data Required

Two types of data are required for input: initial data to perform an analysis, and monitoring data to update design as well as warn of instability. The data input includes:

- geology, geologic structure
- geometry, excavation sequence
- in-situ stress, transient stress
- hydrologic regime
- gas
- temperature field.

These data are common to each method of analysis that is part of the design process. More specific needs for each method are detailed in Table 1 and include material properties. In this regard, data for the entire site cannot be obtained with adequate precision; therefore, an estimate of the variation in properties should be developed during geotechnical characterization as an aid to quantifying uncertainties.

EFFECTS OF DEPTH

The design concerns associated with the more common, "shallow" civil construction differ from those expected at the depths envisioned for construction of the proposed project. There are three primary features of design which reflect these differences.

First, the failure mechanism shifts from a structurally controlled (kinematic) process to a strength/stress controlled process with increasing depth. The failure of openings is driven mostly by gravity at shallow depths. At greater depths the failure mechanism is driven more by the ratio of rock mass strength to the induced stress.

Second, temperature increases with depth and the virgin rock temperature (VRT) might approach 130°F. Thermal stresses associated with VRT levels of 130°F, or less, should not adversely affect the design of openings and support systems. The exception, however, lies in potential increases in rates of rock creep.

Third, the presence of water at depth can be associated with excessively high pressures and flow rates. Either occurrence can lead to the potential for liner failure. Water inflows must be either stopped (e.g., grouting, heavy liners)--which is an expensive and unlikely solution--or drained, a more reasonable scenario.

These three features are considered unique to deep construction and must not be ignored because they may prohibit opening stability and constructibility. Existing design technologies are adequate to handle the issues but are by no means perfect. There are research and development needs that should be addressed. It is essential, in any event, that the issues be recognized at the earliest possible stage of the design process.

SUPPORT SYSTEMS

The design of the support system should be versatile, so that the most appropriate method(s) for support can be determined on the basis of the various rock conditions actually encountered during construction. This approach requires that excavation equipment accommodate installation of a mix of support systems in concert with excavation.

The support systems appropriate for typical categories of ground conditions (or failure mechanisms shown in Table 1) are outlined in Table 2. Within these systems there can be variations. For example, Type 3 ground support may include more closely spaced rock bolts and wire mesh rather than rock bolts and shotcrete. In this case, the variation may resolve a conflict between maximum tunneling efficiency and the desirability of shotcrete.

TABLE 2 Requirements for Typical Support Systems

Category	System
Type 1	Unsupported except for spot rock bolting of occasional loose blocks.
Type 2	Rock bolt pattern (wire mesh required occasionally).
Type 3	Rock bolt pattern with shotcrete layer (and wire mesh).
Type 4	Shotcrete applied immediately after excavation. Rock bolt pattern and wire mesh. Monitoring of deformation. Second shotcrete layer placed after rock has stabilized (if required).
Type 5	Spiling/steel sets. Cable bolts (long). Ground stabilization by grouting (if required). Final encasement (if required). Drainage.
Type 6	Yieldable rock bolts in conjunction with shotcrete and wire mesh. Monitoring of support performance.

However, it should be recognized that within each rock category there may be diverging opinions as to the particular support system to be installed. Therefore, it is important that clear authority be established to direct the contractor as to support requirements for a given condition. This authoritative responsibility, including provisions for appropriate payment, should be assigned either to one individual or to a small group (two or three individuals).

Shafts and Intersections of Openings

Support for shafts and intersections of openings (tunnels/tunnels, shafts/tunnels) will require interactive design and systems similar to tunnels. However, some differences must be considered.

For shafts, the major difference is that the support system would encompass the full circumference of the wall in all cases. During design, particular attention must be devoted to in-situ horizontal stress. To prevent small rock falls during construction, a shotcrete layer can be applied which could also serve as a portion of the support system. Another common safety measure is to bolt wire mesh between the lining and the shaft bottom. Permanent concrete lining will insure long-term stability.

For intersections, the main difference in support design arises from higher stress concentrations than would be encountered in similar rock in a tunnel. The support requirement increases as the angle of the intersection decreases from 90 degrees.

Special Concerns

Groundwater must be accounted for in support system design. For any system that seals the rock and does not allow free drainage, the lining must be drained or designed to withstand the pressure. At depth, the hydrostatic pressure can be high and the heavy liners required to resist the pressures would be extremely expensive. Therefore, drainage and disposal of water inflow should be considered in support design. Drainage should also reduce the amount of free water available in the rock after dynamic loading, a matter of interest for strategic facilities.

The hardening system of strategic facilities is logically related both to the support system and to the rock mass. If a hardened section includes rock bolts, then a portion of that pattern may be used as initial support. If rock bolts are not included, but a hardening system will be installed, then a thin-wall full column support or point anchor bolts may be used. Consideration should also be given to flexible versus rigid support systems.

The geometric aspects of tunnels, shafts, and intersection(s) layouts are important to opening stability. The proximity of multiple openings will affect the concentration of stress around each opening. In addition, the angular relationship of intersections (tunnels/tunnels, shafts/tunnels) affects stress concentrations and the extent of yield zones. Acute intersection angles and multiple intersections should be avoided. When such situations are unavoidable, special support systems such as steel sets and built-up reinforced cribs may be required.

MONITORING FOR INTERACTIVE DESIGN

The initial design may be developed reasonably on the basis of the necessarily limited site and geotechnical information available prior to construction. The various classes of support are predicated on estimates of the behavior of the expected failure mechanisms. However, the geomechanical behavior of the rock as actually exposed during construction, as well as the interaction between the ground and the support, will vary from the assumptions of the initial design. Monitoring and evaluation field instrumentation measurements will permit adjustment of the initial assumptions according to performance, leading to a closer correlation between estimated and actual rock response and support requirements.

The primary elements of initial rock support during construction (viz., rock bolts, mesh, and shotcrete) are readily variable as to spacing or thickness. Consequently, during construction it is quite feasible to modify support quantities based on evaluation of monitoring instrumentation, thereby securing optimum support and economy both in the near term and over extended periods of time.

The monitoring program should be designed to determine the performance of the combination rock/support systems. The program should incorporate the following instrumentation as a minimum:

- convergence points--to verify movements of the supports and rock at the periphery of the opening.
- multiple position extensometers--to verify rock mass movements away from the tunnel surface.
- rock borehole and/or liner pressure cells--to measure stress changes indicative of load transfer.
- piezometers--to monitor water pressure buildup.

RESEARCH AND DEVELOPMENT

Research and development to assist the design of deep underground facilities should include the following efforts:

- Nonborehole geophysical systems (e.g., ground probing radar) need further development for use at the face to identify major geologic features ahead of excavation. Also, surface and borehole geophysics need improvement for more effective site characterization. Electromagnetic (radar) surveys, being sensitive to water, could be used to locate saturated faults in an unsaturated rock environment.
- Case-history information (e.g., stability, rock/support interaction) on deep excavations should be collected and evaluated.
- Constitutive laws need better formulation and/or development for all types of geologic materials, and especially for rock types expected to be encountered at great depths.
- Computer programs for analysis of a jointed rock mass and support response under large displacement (and possibly large-strain dynamic loads with progressive failure by caving and flow) should be developed and the accuracy of computed constitutive behavior should be checked against case-history data.
- High speed, low profile diamond drills need to be developed for instrumented boreholes near the face (just behind the machine).
- Failure mechanics of a jointed rock mass, particularly at high stress levels, require research. Improvements in knowledge of failure criteria and in methods for analyzing the interaction between the rock mass and the installed support system are necessary for designing more effective support.
- Yieldable support elements (e.g., foam concrete, point-anchored, strippable, threaded bolts) require research to determine capabilities for integration into the support system. This is a prime concern for deep facilities in view of the high in-situ stresses expected and the potential for high

dynamic (or quasistatic) loading. Conventional support designs usually feature "rigid" systems (exceptions being yield arches, wood cribs, etc.). Support elements such as full-column and point-anchored rock bolts, cable bolts, shotcrete, concrete linings, and steel sets offer significant resistance to ground deformations and are considered "rigid." In the highly yielding ground that may be expected at great depths, large deformations may cause failure of the support elements and perhaps catastrophic failure of the opening as well.

SUMMARY

The technology exists to design stable underground openings to depths of 8,000 ft. However, this technology is not equivalent to ordinary tunnel design at relatively shallow depths, where sufficient support can usually be marshalled to overcome difficult conditions. Increasing depth requires increasing attention to design principles. Quantitative knowledge of rock mass and support behavior becomes more important, and reliance on the natural support provided by the rock as well as on the installed support becomes essential to stability.

The designers must recognize that the factors affecting opening stability become significant at depth. Therefore, data developed during the site characterization stage must be used to maximum effect in order to avoid early construction difficulties and attendant delays. Interactive design accompanied by instrumentation and monitoring of the rock/support system is essential to design validation and modification.

The instrumentation layout must be planned and implemented in a staged design so that the data expected are provided in a timely manner that allows practical use during construction. Here, deep-mine case histories and related experience are pertinent. Monitoring data should also be used to warn of impending instability.

Finally, it is important that construction philosophies be reoriented towards a deep mining perspective. Deep openings may undergo large deformations, and support systems must work <u>with</u> the ground (i.e., yield) rather than resist the inevitable movement of rock into the openings.

CONSTRUCTION ISSUES

The constructibility of a deep-underground project will be determined, ultimately, by two factors:

- site geotechnical conditions
- facility layout and design.

The site characterization program must account for the geotechnical/geological parameters and physical properties of the rock mass in terms of influence on construction methods and sequence. The layout and design of the facility must permit efficient and rapid performance of excavation and support operations.

GEOTECHNICAL EXPLORATION

Detailed site exploration for construction of a deep-underground facility can be accomplished most effectively by placing a shaft and adit so that the rock conditions to depth can be observed directly, in situ. If time is a constraint and several sites are candidates, it may be desirable to place shafts at each site so that the final decision can be based on in-situ observations. Small-diameter shafts have been drilled to depths of interest at Hot Creek, Nevada (5,500 ft deep; 120 in. diameter) and Amchitka, Alaska (6,150 ft deep; 90 in. diameter).

Exploratory shafts and adits provide direct evidence of the source and magnitude of water inflows. Preconstruction excavation also offers an opportunity to observe the larger-scale rock features that significantly affect construction but cannot be evaluated from borehole data, such as the continuity and waviness of joints and the extent and character of weak zones. For the designer and contractor, the ability to inspect the rock mass and determine significant geotechnical conditions is an important benefit.

An exploratory shaft installed prior to the main construction contract can be used to advantage during construction. It can provide early access to the tunnel level as well as serve ventilation and mucking operations throughout the construction period.

Site Characteristics

A major purpose of the geotechnical exploration program is to determine site characteristics that bear on excavation and support procedures. In selecting a site or locating a facility at a given site, the occurrence of certain conditions should be viewed as distinct disadvantages for construction. Even if not defined as "fatal flaws," these conditions can have a substantial negative impact on construction operations, cost, and schedule. Therefore, if possible, project siting should not be considered in areas that feature:

- major aquifers.
- heavy squeezing or swelling characteristics (e.g., wide fault zones, plastic shales).
- gassy formations (e.g., methane).
- virgin rock temperatures above 100° F.

Large quantities of water at depth are difficult to handle and are hazardous when suddenly encountered during construction. Siting the project in or near sources of substantial water such as major aquifers and heavily faulted ground should be avoided. When fault zones must be penetrated, the opening should be oriented to minimize distance in faulted ground. Heavy squeezing and swelling of the host rock impedes the performance of most tunnel boring machines with rigid, cylindrical bodies. Gassy formations are dangerous and slow productivity because extensive safety precautions are required to protect crews and equipment. High temperatures increase the ventilation and cooling modifications necessary to maintain the efficiency of the construction operation.

Other conditions that will adversely affect construction, but perhaps to a lesser extent than those indicated above, include the following:

- stress slabbing, violent spalling, or rock bursts in highly stressed, brittle ground.
- extensive ravelling and slaking.
- low volume water inflows at high pressure (extensive grouting of small fissures to reduce inflow rates to meet project requirements).

None of the conditions noted will preclude construction provided that sufficient time and finances are available to manage the consequences. Still, from a construction standpoint, the most desirable course is to reject sites where major occurrences of the conditions are judged likely to exist, based on available geotechnical information.

Minor occurrences of any of the conditions can be accommodated. However, the presence of water or gas always warrants special consideration for potential to impede construction as well as to create problems during operation of a facility.

The "ideal" location would be an area with a relatively low, average ambient surface temperature and a low or average subsurface temperature gradient. The subsurface would be free of water and gas, the rock would be competent and machine boreable, and the rock mass would be free of major discontinuities. These favorable characteristics would be predictable and exist throughout the entire site.

FACILITY LAYOUT AND DESIGN

The design and layout of an underground project is a primary means of promoting efficiency, economy, and safety in construction. Constant attention to this relationship is essential to successful completion of the facilities envisioned. Some of the actions important to complex construction operations at depth are:

- Layout the facility so that each shaft system (i.e. pair of shafts) will serve as many underground headings as possible.
- Design each shaft system to handle (a) maximum muck hoisting, (b) maximum material servicing, (c) maximum personnel servicing, (d) maximum ventilation, and (e) special, major heavy/large equipment transport, including operational requirements.
- Estimate the average advance rate for multiple headings served from a single shaft at 50 percent of the rate that would be achieved under single heading, surface portal conditions.
- Maximize use of raise drilling, reaming, or slashing methods for shafts when ground conditions are appropriate.
- Avoid hydrostatic liners in large openings.
- Establish rail haulage at less than one percent grade.
- Plan grades for equipment operation within suitable limits: (a) -15% and +10% maximum desirable grades for LHD ramp, (b) -20% and +15 % maximum allowable grades for LHD ramp, (c) 20% maximum desirable grade for tunnel boring machine.

Safety

Planning for the health and safety of personnel begins early in design development for the preconstruction through post-construction stages of a project. The issue is inherent in the phased, integrated approach proposed for geotechnical exploration, design, construction, and equipment selection. However, the scope and schedule of this workshop permit only the briefest acknowledgment of questions related to safety. Therefore, a partial list of design objectives for stability and constructibility is presented here as a means of highlighting the range of factors to be accommodated in plans for a healthy and safe working environment:

- Layout parallel openings with connections, where possible, to aid ventilation and provide emergency escape ways.
- Plan machine mining for shafts, if possible.
- Provide for immediate installation of adequate initial support.
- Maintain heat (wet-bulb temperature) at the face within acceptable limits; prepare contingency stand-by power and evacuation plans.
- Limit encounters with very highly stressed, brittle rock (potential for severe popping or bursting).
- Minimize exposure to heavily faulted ground where sudden, high inflows of water could be encountered; probe for water where expected.
- Monitor the presence of radon and other gases and plan for adequate dilution; avoid siting in gassy formations, if possible.

Hazardous situations may develop with little advance notice and escalate rapidly. Even though the probability of occurrence may be small, it is essential that trained personnel and appropriate equipment and supplies be readily available to handle emergency conditions.

EFFECTS OF DEPTH

At the depths envisioned for this facility, conditions will differ from those associated with common, civil construction. Depth produces changes in the rock environment and imposes consequences for project execution that may influence construction requirements, efficiency, and costs. The factors of concern at depth include temperature, in-situ stress, groundwater inflow, rock quality, and logistics. Their effects on the construction effort can be summarized as follows:

- Temperature--rising temperature increases cooling and ventilation requirements and decreases worker efficiency.
- In-situ stress--high in-situ stress increases the potential for stress slabbing (formation of new fractures) and rock bursts (violent rock failure) around the advancing opening.
- Groundwater inflow--increasing pressure exacerbates the volume and rate of groundwater inflows. High-pressure flows encountered suddenly can halt construction and flood the excavation; pumping costs for significant quantities will be high. Large inflows may bring additional heat into the tunnel, raising the wet bulb temperature beyond the desirable range by the process of evaporation. Groundwater inflows also tend to reduce stability of the rock blocks surrounding an opening and contribute to muck handling problems.

  Decreasing permeability may occur with increasing depth at some sites and significantly mitigate groundwater inflows. If reduction of inflow were necessary in low permeability rock, grouting at high pressure and low viscosity would be required.
- Rock quality--improvements in rock quality typically develop with depth, including an increase in joint spacing and tightness and an absence of weathering, relief joints, and other surface features. However, some structural features may penetrate deeply, such as large fault zones which can result in heavy squeezing at depth.
- Logistics--increasing difficulty in access for exploration purposes may result in more unknowns and greater risk until access at depth has been achieved. The time required for shaft sinking and shaft operation will lengthen, with progressive impact on the project schedule. Changes in layout may be necessary for construction efficiency.

It should be emphasized that the benefits or problems associated with a deeper facility are strongly influenced by the local site conditions, such as geologic structure, rock strength, and temperature gradient with depth. For example, at some sites the strength of the rock will be sufficient to prevent stress slabbing, even though the facility is deep. The variation in these conditions from one site to another, at the same depth, may be greater than the variation with depth at a single site.

Several factors of concern to construction at depth merit discussion in more detail. They are temperature, ventilation, and in-situ stress.

Temperature and Ventilation

In underground construction, the temperature level is influenced by several factors. The geothermal gradient at a given site determines the virgin rock temperature (VRT) at a given depth. To the VRT must be added the significant amounts of heat generated by electrical machinery. For example, a tunnel boring machine will produce about 20 kW-h of heat energy per ton of rock excavated--or 6 million Btu per hour for 100 ft of 18-ft diameter tunnel per day. Heat also flows from rock strata, broken rock, and fissure water if the VRT is above the ambient air temperature.

Heat criteria based on human physiology indicate that a maximum design work area temperature of 86°F wet-bulb (WB) can be well supported. The temperature ranges (°F) defined for work areas are as follows:

< 80° WB	Worker efficiency is 100 percent.
80° to 86°	The "economic" range. An acclimatized miner can perform effectively.
86° to 91°	The "safety factor" range. Corrective measures should be applied if temperatures are in this range.
> 91° WB	Risk of heat stroke climbs dramatically. Only light-duty, short duration work should be expected in temperatures greater than 91° WB.

For facilities with the potential for elevated temperatures at depth, the heat must be removed or isolated to keep work area temperatures under 86°F (WB), the "economic" range. Thus, it is most desirable to site the facility in strata with a VRT of less than 86°F. The 86° to 100°F range is acceptable, but some air-conditioning would be required in long, dead-end, rapidly advancing headings. Construction in strata with VRTs at about 100° to 125°F is certainly possible but apt to be very costly.

Ventilation is an immediate construction concern, requiring that a primary ventilation circuit be set up quickly. The procedure involves driving at least two headings or shafts from the surface and connecting them underground at the proper depth. A fan is then placed in the circuit, which functions to provide fresh air for the auxiliary fan system. Quantity is determined by summing the requirements of the individual headings. In mining, drift and shaft sizes are often specified to limit the fan operating point to a 25 to 30 in. water column.

Current ventilation technology is adequate for constructing a deep facility. The cost and complexity of the system will depend on the anticipated heat load. Planning for ventilation will depend on the design and layout of the facility.

In-Situ Stress

The effect of stress on stability and excavation progress must be viewed with respect to the strength of the intact rock. Stress slabbing behavior will begin to occur in brittle rocks when the unconfined strength of the intact rock is less than approximately five times the maximum in-situ stress (taken as equal to the overburden stress, in many deep projects). At this strength level, the slabs may form along the intact rock and some combination of a preexisting joint, foliation feature, or bedding plane. More pronounced slabbing occurs when unconfined strengths are less than approximately two to three times the overburden stress. At this ratio, fracture through the intact rock alone is likely.

The intensity of the popping or slabbing of the rock is a function not only of the strength/stress ratio but also of the brittleness of the rock and the total strain energy that is released as the rock fractures. For a given strength/stress ratio, the stiffer, higher strength rocks will release more energy and result in more dynamic spalling. In rock with pre-existing fractures, the intensity of the slabbing will be less than in the more intact rock, even though the slabbing and loosening might take place at a lower threshold of in-situ stress.

Tunnels can be constructed in ground subject to stress slabbing if appropriate excavation and support procedures are applied. TBMs can be used successfully if the cutterhead and mucking system are designed to handle slabs of the size possible under spalling and stress slabbing conditions. Short, movable shields may be preferable to long, fixed shields on TBMs. The support must be capable of holding the fractured rock in place. Rock bolts or dowels, mesh, and shotcrete can be used to control stress slabbing and provide support. Under stress slabbing conditions, particularly in a deep excavation, the support must be installed close to the tunnel face to protect against spalling and to minimize loosening of slabs.

EXCAVATION AND SUPPORT

In view of the size and complexity of the proposed facility, which are factors compounded by the depths envisioned, other deep underground projects should be surveyed as potential sources of useful information. For example, in North America, South Africa, and India, mines operate at depths similar to and several thousand feet greater than the maximum anticipated here.

In Europe, and to a lesser extent in North and South America, tunnel construction in mountainous areas has involved ground cover that is deep by the standards for this project. For example, the old Connaught Railroad tunnel and the new Rogers Pass tunnel are at depths of 4,000 ft in schists, with foliation trending across the tunnel axis. The Connaught tunnel was excavated largely without support, although a protective lining was later installed to prevent falling of rock pieces loosening in the tunnel arch. The rock showed no evidence of significant stress problems. In a different type of project on Amchitka Island, chambers were excavated at a depth of 5,000 ft without spalling problems related to high stresses.

For the most part, TBMs with long, fixed shields have not performed well in deep tunnels in which the ground was subject to squeezing and slabbing induced by stress. Either squeezing or loosening of slabs around the perimeter of a long shield can cause the TBM to stall. Furthermore, once the slabby rock emerges from behind the tail of the shield, it is often so loosened that it is difficult to support in place. In South Africa, operation of TBMs at great depth (i.e., 9,000 ft) was unsuccessful due to effects of both temperature and stress.

Recently, TBMs with short shields and the capability of placing support close to the cutterhead have performed well in ravelling and squeezing ground. In the Stillwater tunnel, at a depth of 2,000 ft in a ravelling and moderately squeezing shale, progress over a period of months averaged in excess of 150 ft per day using a TBM with a short canopy, whereas a TBM with a long shield had been slowed and was finally unable to advance in the same ground conditions.

For shaft sinking, the diversity of project experience is more limited and contractor experience is limited even more so. Generally speaking, only a few contractors in North America have sunk single lift shafts to depths greater than 6,000 ft.

Tunnels

The facility should be designed to take advantage of the capabilities of tunnel boring machines. Long runs of tunnels with circular cross section and constant diameter are desirable. There may be advantages if pairs of tunnels are driven together, with cross adits connecting the two. For example, an opportunity may be provided to perform both the excavation and lining operations simultaneously, at different locations in the tunnel. Further, access to and egress from the heading is improved, groundwater inflows are more readily controlled, exploration can be carried out ahead of the tunnels, and ventilation may be enhanced.

Generally, the ability to place ground support immediately behind the face becomes more important in a deeper facility because the potential for instability increases with depth. Fully resin-grouted or friction anchor bolts can be installed immediately behind the cutterhead of the TBM. Wire mesh or cables tied to the grouted bolts is one means of providing protection from dynamic effects. High strength, wire fiber-reinforced shotcrete also helps to control spalling as well as to prevent loosening of slabs. A silica fume additive is useful for rebound control.

In rock subject to spalling and fracturing, and in faulted ground, it is desirable to have the capability to place shotcrete close behind the cutterhead of the TBM rather than having to delay placement until the trailing gear has passed. However, shotcrete is not normally placed around a TBM, particularly in small-diameter tunnels, because of dust, space limitations, rebound buildup on the machine, and limited visual ability to monitor placement. Thus, when rock bolts alone are inadequate and some intermediate support between the bolts is required near the face, the contractor often must switch from bolts to steel ribs rather than being able to add shotcrete and retain the rock bolts. This change involves different equipment and requires a significantly different construction technique. Switching back and forth between the methods results in delays as equipment is removed and replaced and in low efficiency as crews alter their routines.

There is a contradiction here, because a tunnel lining system that relies on bulk materials, such as shotcrete components, may be preferable for a deep facility. Large lining elements such as steel ribs and precast segments require increased handling time in the shafts compared to bulk materials.

Even though it may be necessary to install additional support at a later time for the permanent requirements of the facility, it would appear desirable to use the initial support for permanent support to the maximum extent possible. Efforts might well be directed toward developing and testing a support system that can be installed efficiently and yet has the ductility and toughness required to withstand large deformations during loading.

Shafts

Shaft sinking performance can greatly affect the total project schedule. The initial shaft must be sunk blind and will be on the critical path from start to finish. Whether subsequent shafts are sunk blind or constructed by one of several other means will depend on rock conditions, preferred diameter, and schedule constraints.

An exploration access shaft would be the first to be constructed. Another shaft, and most likely a pair, would be required for ventilation adequate to accommodate high advance rates for multiple tunnels at depth. The shaft(s) could also serve for mucking and service operations. To achieve full production at the tunnel level as soon as possible, a shaft for exploration and one for ventilation could be blind sunk simultaneously.

In soft rock, the fastest method to put down a small-diameter shaft is by blind shaft (large-hole) drilling. The diameter that can be achieved decreases as depth and rock strength increase. Surface drill rigs will cut rock up to 30,000 psi, but only at small diameters and high costs. The diameter possible at a given depth, even though suitable for exploration purposes, may be too small to permit adequate ventilation to remove heat.

Blind shaft sinking by conventional (drill-and-blast) means is possible at diameters up to approximately 33 ft and to depths of 8,000 ft. This method is suitable for all the rock strengths considered here. The sinking rate would probably reach 8 or 9 ft per day. With proper plant, the sinking rate is relatively constant, i.e., not diameter dependent.

A blind downhole boring machine is in the development stage but the technology is not fully proven. Such equipment is expected to perform effectively in rock up to 25,000 to 30,000 psi compressive strength. Shaft diameters of 22 ft and sinking rates of up to 20 ft per day (twice the rate of conventional sinking) should be possible with this technology. Basically, like conventional sinking, the machine would work to a maximum depth of 8,000 ft, at which point hoisting limitations would be reached.

Once one shaft is sunk, is may be possible to construct a second shaft using raise drilling, reaming, or slashing methods, depending on ground conditions. Single or multiple-pass enlargement is faster than conventional sinking and requires less heavy plant. For a deep shaft, it will be necessary to install drill stations at intermediate levels. Raise and reaming equipment has been used for shaft depths to a maximum of 2,500 ft, but poor accuracy of pilot holes is a limitation for methods requiring their use. However, technology now being developed to drill accurate pilot holes should be available when required. Raise and reaming equipment has been used successfully in rock with compressive strengths as high as 50,000 psi. In soft rock, raised or reamed shaft diameters of 20 ft are realistic; in hard rock, 15-ft diameters are possible.

In mechanically excavated shafts, the primary lining would be applied after completion of excavation and the method of application would depend on lining design. Raise, reaming, and blind drilling techniques would be used only in favorable ground and blind boring or conventional methods would be selected for use in poorer conditions.

As the depth of the facility increases, the length of tunnel driven from a given shaft should be increased to achieve an efficient operation. Multiple headings in a hub-like arrangement might be driven from a single shaft. Alternatively, fewer but longer tunnels could be driven from the shaft.

Multiple, long headings, if simultaneously driven, will present large muck hoisting and ventilation requirements. Thus, it is expected that the diameter of the shafts required will increase with the depth of the facility.

RESEARCH AND DEVELOPMENT

The construction technologies can be advanced significantly by research and development that is accompanied by demonstration projects. It is anticipated that substantial progress could be achieved in sufficient areas so that the results could be applied to construction projects starting within a few years. Some of the most important requirements are as follows:

- Rapid methods to sink shafts.
- TBM capable of dealing with violently spalling ground.
- TBM that allows application of steel fiber imbedded shotcrete immediately behind the face.
- TBM that can perform effectively when rock hardness exceeds 30,000 psi compressive strength.
- Support systems that are easily installed near the face and have large displacement capabilities.
- Directional control of drilled pilot holes.
- Feasible means to use the heat of evaporation to cool the environment and means to transport liquified air into the headings to supplement ventilation.
- Improved techniques for heat exchange (e.g., U-tube) in vertical shafts and for transporting ice underground pneumatically, in order to reduce pumping of condenser cooling water.

SUMMARY

The major factors affecting constructibility deep underground are geotechnical conditions at the site and the design and layout of the facility. The characteristics of the rock mass influence construction method and sequence. Among the more adverse features are major aquifers, heavy squeezing or swelling behavior, gassy formations, and highly stressed ground subject to violent spalling. Facility design and layout influence performance of excavation and support operations. Considerations include shaft systems for multiple headings, shaft capacity for maximum transport and mucking, grades for rail haulage and equipment operation, and parallel openings with connections to aid ventilation.

Increasing depth is accompanied by changes in the rock environment that can influence construction requirements, efficiency, and costs. Factors meriting specific attention are temperature, in-situ stress, groundwater inflow, rock quality, and logistics. For example, rising temperature increases ventilation requirements and decreases worker efficiency; high stress increases the potential for slabbing and rock bursts; volume and rate of groundwater inflow is exacerbated by increasing pressure; structural features such as large fault zones can result in heavy squeezing; and limited access for exploration increases the possibility of unknown conditions.

The facility should be designed to accommodate excavation with tunnel boring machines. TBMs with short shields may be more effective than machines with long, fixed shields. Long runs of tunnels with circular cross sections and constant diameter are desirable. Driving pairs of tunnels with connecting cross adits may benefit exploration, groundwater control, and ventilation. The ability to place support immediately behind the face is important because the potential for instability increases with depth. A lining system that relies on bulk materials rather than large components may be preferable.

The construction technologies should be improved for excavation and support operations at depth. Substantial progress can be achieved through developments such as TBMs capable of dealing with violently spalling ground, more rapid methods to sink shafts, efficient installation of support systems with large displacement capabilities, and directional control of drilled pilot holes.

EXCAVATION EQUIPMENT AND SYSTEMS

This working group was assigned the task of assessing the technical feasibility of mechanical excavation systems for the construction of deep-underground facilities. Many factors affecting equipment design and system selection were considered with particular reference to construction technology. Therefore, concepts developed herein should be reviewed in concert with those presented in preceding parts of this report, particularly the chapter dealing with construction.

In addition to the general assumptions adopted as a framework for the workshop, the group assumed that the underground facility would be constructed with several distinct modes of excavation. Equipment requirements were considered for each of four categories of excavation, as follows:

- tunnels--more than 1,000 ft in length.
- crosscut passages and intersections--short chambers or tunnels less than 1,000 ft long.
- access shafts--vertical opening to surface, temporary for construction.
- internal shafts--temporary or permanent shafts between levels, or cylindrical openings required by facility plan.

Types of cutting machines, bit or tools, and muck removal and excavation support equipment are considered for each mode of excavation. State-of-the-art construction methods are discussed, as well as potential equipment modifications and possible applications of emerging technologies.

TUNNEL CONSTRUCTION

Excavation Equipment

Four types of mechanical equipment were considered for potential use in tunnel excavation. The types, all state of the art, are full-face tunnel boring machines, partial-face tunnel boring machines, roadheaders, and impact breakers.

FULL-FACE TUNNEL BORING MACHINES

A tunnel boring machine (TBM) employs a circular cutterhead structure to which either drag or disc-type cutting tools are attached. The circular structure is rotated and thrust at the rock surface at the heading, causing the cutters to penetrate and fracture the rock. Torque and thrust reaction forces are taken through a structural frame to an anchoring system which braces by gripping the tunnel wall.

TBMs have been used efficiently in excavating soft to hard rock--i.e., Rock Quality Designation (RQD) values from 25 to 100 percent and uniaxial compressive strengths from 2,000 to 35,000 psi. TBMs are generally designed for optimal performance in geological environments with limited variations in rock and rock mass characteristics. Some "hybrid" machines designed to accommodate a wide variety of rock conditions have been used also, but with varying degrees of success. Thus, the site selection process should identify and exclude locations with widely varying rock characteristics.

The technology exists today for efficient excavation of circular headings at average advance rates between 100 and 200 ft per day. On a specific project, the advance rate will depend on the design of the excavation system, the tunnel lining required, muck haulage capacity, contractor scheduling, and human factors. To allow for the most rapid advance, the bored tunnel should be 10 ft in diameter at a minimum.

Recent modifications incorporated in TBM system designs include the following:

- disc cutter arrangements which reduce radial loads on the main bearing, increase penetration, and reduce cutter wear.
- rear-mounted cutters which can be replaced from the rear of the cutterhead, decreasing excavation delays.
- dust control systems which incorporate double dust shields with suction on the rear shield.
- hydraulic systems which minimize space and maintenance requirements and heat production.
- stepped or variable drives which provide a range of cutterhead rotation rates and may increase penetration in rock masses where machine progress is not limited by available torque.

For long tunnels with gentle alignment curves (radius greater than about 300 ft for an unshielded machine) and grades not exceeding 20 percent, a full-face, disc-cutter-type TBM is the most viable excavator. Trailing floor components are generally of limited flexibility, however, and larger radii curves (about 500 to 600 ft) may be required to allow adequate clearance for the equipment.

For ramps and slopes, TBM design can be modified to provide efficient performance at grades up to about 27 percent (15 degrees) downgrade and about 100 percent (45 degrees) upgrade. Upgrade excavation on steeper slopes can be accomplished with blind shaft boring equipment, which is discussed later in this chapter. Excavation in an upgrade direction is preferable because it eases muck handling and water disposal and reduces power requirements.

PARTIAL-FACE TUNNEL BORING MACHINES

Partial-face TBMs utilize disc or pick-type cutters but attack only part of the rock face at the heading at any one time, using a horizontal or vertical sweeping motion to complete the full face. Circular cross section, partial-face cutting equipment has been used successfully in Europe. One partial-face machine which cuts a rectangular opening currently is undergoing trials in Australia. Because only a few cutters are in contact with the rock at any time, thrust and torque requirements are less than for a full-face TBM. Therefore, compared with a full-face machine, partial-face TBMs can be lightweight and highly maneuverable equipment. However, the limited installed power results in correspondingly low advance rates. This equipment may be used more efficiently in shorter tunnels and crosscuts, where maneuverability and short mobilization time are of prime importance.

ROADHEADERS AND IMPACT BREAKERS

A roadheader is a mobile, partial-face boring machine. Cutting tools are tungsten carbide picks on rotating cutterheads mounted at the end of one or more cantilevered booms. In typical use, the machine is not braced against the tunnel walls. For circular openings in relatively massive, strong rock, roadheaders cannot be sufficiently productive to compete with full-face equipment and pick costs are likely to be high. However, if a noncircular cross section is required or mobilization time is short, roadheader excavation may be preferred. In lower strength or less massive rock, where support installation may control the rate of advance, roadheaders may be competitive with full-face equipment.

Impact breakers are percussive machines which break rock by mechanical impact. Expected low advance rates indicate that no serious consideration should be given to this type of tool, other than for trimming operations.

Research and Development

Overall, a full-face TBM is clearly recommended for most efficient excavation of tunnels. Thus, subsequent comments on tunnel construction equipment are directed only toward full-face, TBM-based systems.

Significant increases in TBM excavation rates can be achieved by implementing equipment developments and applications of emerging technologies. Areas for particular attention include cutterhead power, cutting tools, main bearings, fatigue resistance, shield design, water-jet assisted cutting, continuous monitoring, and robotics.

CUTTERHEAD POWER DENSITY

Higher penetration rates result in substantial increases in cutterhead torque and power requirements. At present, the most significant factor limiting penetration rate is the amount of power which can be installed in the space available at the face. Although some success has been noted recently in increasing power at the face, developments and basic changes in motor and drive mechanism design are needed to increase the power density of the cutterhead.

CUTTING TOOLS

For the foreseeable future, the single disc cutter is likely to be the principal cutting tool for TBM excavation. Significant advances in cutter design are possible for increased excavation efficiency. Power requirements for excavation (hp hour/ton of rock) can be substantially reduced by incorporating high thrust cutters which permit larger spacing between kerfs and fewer cutters on the cutterhead. Increased cutter disc life and resistance to abrasive wear are possible with the use of new alloys for disc rings and the expected development of improved single disc carbide-insert cutters. In addition, improvements in the design of center cutters are desirable to reduce high wear rates and scuffing associated with the tight rolling radius. Attention also should be directed toward improvements in bearing seal design to extend cutter life.

MAIN BEARINGS

When TBMs are considered for excavation of very long tunnels, the need for superior quality and more easily changed main bearings becomes imperative. In current machines, replacement of a failed main bearing requires a 4-week minimum shutdown. Improved conventional bearings, or possibly hydrostatic bearings, must be developed. Furthermore, changes in the machine configuration are required to permit rapid replacement without over-excavation or pulling the machine from the face.

FATIGUE RESISTANCE

Faster cutterhead rotation rates and higher thrust produce cutterhead and machine vibrations with higher amplitude and frequency. The potential for fatigue problems will increase, particularly when machines are used for longer drives. Structural plate alloys with increased toughness should be incorporated into cutterhead design. Attention also should be given to saddle design details because saddle bolts fail with increasing frequency on machines with high rotation rates.

SHIELD DESIGN

Under conditions of high in-situ stress, ground squeezing around the TBM can slow advance rates or stall progress completely, locking the machine in place. Improvements in the design of TBM shields are needed to facilitate operation of equipment in squeezing ground conditions.

LOW PRESSURE, WATER-JET ASSISTED CUTTING

The use of low pressure (as low as 2,000 psi) water jets to assist disc cutting results in significantly reduced cutter forces. Force reduction is not particularly significant in softer rock where high penetrations can be realized with unassisted cutting. However, in harder rock the force reduction can be a major benefit, allowing increased penetration rate by a machine with a given torque capacity. Water-jet assistance may be especially useful at gage and center cutter positions where it may extend cutter life. Pumps required to generate low water pressures are commercially available and of proven reliability for long periods of operation.

CONTINUOUS EQUIPMENT MONITORING

The advance rate of a TBM depends both on the rate of penetration and on equipment availability. For recent, well-run projects, actual boring time is typically only about 50 percent of total shift time. Perhaps only 20 percent of the downtime is attributable to service and repairs of TBM system components, but this figure might be reduced by incorporating instrumentation to detect problems and allow maintenance before breakdowns occur. Redundant systems, which can be automatically utilized as required, can also be incorporated into TBM system design to increase equipment availability.

ROBOTICS

Remotely operated and robotic systems can be incorporated for various purposes to increase reliability and reduce the number of required personnel. The following applications for robotic systems are particularly interesting:

- cutter changing
- automatic steering control
- automatic gripper reset
- automatic support system installation
- equipment maintenance (e.g., lubrication).

Rock Support Installation

INITIAL SUPPORT

When initial support is required to ensure stability of the heading, the following equipment can be used for installation:

- o hydraulic rock bolt drills mounted on the TBM to install bolts within about 8 ft of the dust shield.
- o mechanical erectors to facilitate installation of steel sets and structural fabric ("weld mesh") lagging within a finger shield about 6 ft behind the dust shield.

Structural fabric has been used in Australia and West Germany for its ability to yield while containing failed rock, but such fabric has not been used extensively in the United States. This technology should be considered and demonstrated prior to construction of the facilities discussed here.

Particular attention should be given to optimizing the rate of erecting steel sets within the trailing fingers.

It will be noted that shotcrete is not mentioned as a component of the initial support system. Recent experience with shotcrete applied in the vicinity of a TBM has resulted in considerations of equipment maintenance. The problems encountered with current technology suggest that application of shotcrete in close proximity to a TBM is undesirable and should be avoided.

FINAL LINING

In some rock masses, a final tunnel lining can be erected near the active heading, precluding the need for initial support installation. For example, precast-concrete segment liners can be placed immediately behind the TBM gripper locations, and erection equipment can be provided. Alternatively, conventional cast-in-place liners with steel fiber or rebar reinforcement can be placed with collapsible or telescoping formwork.

Work has been progressing on the conceptual development of extruded tunnel lining systems both in the United States (slip-form type) and in West Germany.

The less sophisticated German design has been used in a 22.5-ft diameter soft-ground tunnel.

Placement of a final lining is an operation that should be located 1,000 to 3,000 ft behind the TBM trailing floor and be "decoupled" from the tunnel excavation process. Development of a viable lining system that is close-coupled to the rear of the machine is possible, but not likely to be accomplished within the next five years.

Anticipated Advance Rates

With implementation of the suggested equipment modifications, advance rates currently achieved can be increased significantly. Assuming that horizontal and vertical muck removal systems are designed for "no-delay" haulage, that initial support requirements are minimal, and that no delay occurs in conjunction with placement of arch concrete, then an estimate of TBM performance can calculated (Table 1).

TABLE 1 Potential Performance of a Modified Excavation System[a]

Uniaxial Compressive Strength of Rock ksi	Estimated Rate of Penetration[b] ft	System Utilization %	Average Advance Rate ft/day
5 to 10	28 to 35	35	235 to 294
10 to 20	25 to 28	45	270 to 302
20 to 30	18 to 25	55	238 to 330

[a]An 18- to 20-ft diameter TBM with 2,000 hp installed power and an energy consumption rate of about 3 hp-hr/ton.
[b]Rate of penetration limited by assumption of installed power.

The rates of penetration for the three ranges in rock strength listed in Table 1 are estimates based on boring experiments conducted at the Colorado School of Mines. The system utilization values are estimated to include time from the start of operation with the trailing floor until completion of the tunnel. Advance rates are similar for the cited rock strength groups, and an overall average of 250 to 300 ft per 24-hour day is potentially achievable. Such an achievement would present a considerable challenge at great depths and high ambient temperatures. For tunnels at depths less than 5,000 ft, however, advance rates in this range are a reasonable goal for the 1990-1995 time period.

EXCAVATION OF CROSSCUTS AND INTERSECTIONS

Types of Equipment

Five types of mechanical excavation equipment are considered for efficient excavation of crosscuts and trimming operations at intersections. They are roadheaders, multipurpose boring machines, mobile miners, partial-face mobile excavators, and water-jet equipment.

ROADHEADERS

Roadheaders are machines equipped with rotary cutterheads, either drum or milling type, mounted on one or more boom arms. This equipment is highly flexible and good for small, intricate jobs. A roadheader unit is easily moved and can cut any cross-sectional shape. Reaction to the cutting forces is supplied by the dead weight of the equipment. Roadheaders are not usually braced against the excavation walls; some gripping mechanism would increase cutting efficiency but at loss in flexibility.

Single-pass operations can cut 6- to 20-ft openings. Larger drifts can be excavated with shield-mounted roadheaders or heading and bench construction techniques. Typical cutting tools are picks, and utilizations of less than 30 percent are commonly achieved on jobs where support installation is required.

Currently, roadheaders are operated in rock with uniaxial compressive strength less than about 15,000 psi. If the rock is massive, the limiting uniaxial compressive strength for efficient excavation can be as low as 5,000 psi. The disadvantages of roadheader excavation include slower advance rates, high cutting tool costs, and the tendency for heavy machines to "cut up" the invert during mining. Roadheaders will be most useful for low volume, intricate shaping or trimming in rock of moderate strength.

MULTIPURPOSE (FULL-FACE) BORING MACHINES

Multipurpose boring machines (MBMs) are short, maneuverable tunnel and shaft boring equipment currently in development. The MBM, intended to be self-launching and to be used in soft to hard rocks, includes sidewall grippers for reaction of cutter forces. This equipment is remotely operated, so that personnel are not exposed to hazardous conditions or unsupported ground and ventilation requirements may be reduced.

The MBM is designed for horizontal, sloped, and vertical excavation. Muck removal equipment is required for uphill excavation where grades are up to about 60 percent (30 degrees). Grades greater than this will "self-muck" by gravity. The maximum downgrade for excavation is about 27 percent (15 degrees), a limitation imposed by the machine conveyor in current use. Abrupt grade changes can be accomplished with a relatively small required radius, about 80 ft for 6- to 8-ft diameter headings. The existing design is for machines in this diameter range only. If the size were to be increased, some flexibility would be lost.

PARTIAL-FACE MOBILE EXCAVATORS

Partial-face mobile excavators are machines which use disc cutters on a partial-face cutterhead. The cutterhead rotates on an axis and can be moved transversely to cut a rectangular opening. Anchoring is provided by side and/or crown and invert hydraulic grippers. One type of partial-face excavator in current use is the mobile miner, which was developed to excavate a rectangular opening 12 ft high by 20 ft wide. Other units are designed to cut openings from 7 ft high by 10 ft wide to 14 ft high by 22 ft wide. Two-pass operations are possible for higher openings.

The mobile miner leaves a flat invert and can excavate efficiently both tunnels and slopes to 36-percent (20 degrees) grade. This equipment is very flexible and well suited to either hard or soft rock. Partial-face equipment will be most effective for side entries with lengths too short to justify mobilization of full-face units.

WATER JETS

Water jets are employed frequently for operations in uraniferous sandstone, e.g., drilling roof bolt holes. The equipment performs best in porous or soft rock, although high-pressure water jets have been applied successfully for slotting granite dimension stone. Minimal amounts of water are required at high pressures, and the support equipment is compact and easily moved. Power requirements are high, so that water jets alone cannot be considered competitive with other equipment for large volume excavation.

The use of water-jet assisted bits for drilling and cutting is a proven approach to excavating rock and will facilitate excavation of intricately shaped openings in areas where damage to the surrounding rock must be minimal. Excavation with water-jet assisted drills and slotting equipment generally results in bit life that is many times greater than that for conventional tools.

Research and Development

To improve the operating efficiency of crosscut excavation equipment, attention should be devoted to implementing the following developments and modifications:

- Water-jet assisted roadheaders for softer rock.
- Bracing mechanisms for roadheaders and water jets to provide increased performance in harder rock.
- Hard-rock roadheader with disc cutters and, perhaps, water jets.
- Increased flexibility in partial- and full-face boring equipment.
- Partial-face mobile excavators for larger section, short-length tunnels.

ACCESS SHAFT EXCAVATION

Types of Equipment

Various types of mechanical equipment can be considered for use in excavating the 3,000- to 8,000-ft deep, 20- to 25-ft finished-diameter shafts to be used for construction access. In the following discussion, the terms "drilling" and "boring" are not interchangeable. "Drilling" refers to equipment with the power supply located remotely at a derrick and transferred to the face via a drill string or pipe. "Boring" indicates equipment with a power supply downhole, part of the cutting equipment.

BLIND DOWNHOLE DRILLING

Large-diameter drilling may be a possible technique for excavating access shafts. Using a reverse circulation, air lift method of muck removal, shafts have been drilled in a single pass at 10-ft diameter and 8,000-ft depth in Amchitka, Alaska, and at 14-ft diameter and 2,460-ft depth in Western Australia. Multiple-pass shafts have been drilled at 25-ft diameter and 1,680-ft depth in Holland (1954-1959). These multiple-pass shafts were completed in 40 to 43 months.

Drilling shafts is inherently safer than conventional sinking because no personnel enter the shaft until it is fully lined. Moreover, drilling can be the only practical construction option in some geological conditions, i.e., very soft ground or very wet conditions. The water (or mud) in the shaft supports the walls and stems the water inflow by virtue of its hydrostatic head. Formulating the mud to match the chemistry and requirements of the rock is an established science.

At least two rigs have been built with power (to 0.5 million ft-lbs torque and 2.0 million lbs lift) sufficient to drill large holes at an economical rate. However, the practicality of building larger and larger rigs is questionable. A disadvantage of the drilling system is the requirement that all power to the rock face must be transmitted through the drill string. The cost of a few thousand feet of large-diameter drill pipe will exceed the price of the drill rig.

One fundamental limitation of the blind shaft drilling technique is the accuracy of the shaft. In general, a shaft proceeds in an ever expanding spiral and deviation control is totally passive. Shaft tolerances are especially critical if the ultimate use of the shaft involves high speed hoisting. Maintaining true verticality within 0.25 degrees is a function of geology, equipment, crew talent, and sometimes luck.

In summary, drilling may be a viable option at diameters of 12 to 16 ft and depths of 3,000 to 5,000 ft. At sizes and depths beyond these, blind drilling probably reaches its economical and feasible limits.

BLIND DOWNHOLE BORING

The use of a downhole boring machine--similar to a TBM operated vertically--is, in theory, an option for conventional shaft construction. This manned system uses all the established conventional techniques except that the drilling and blasting operation is replaced with a mechanical full-face or partial-face rock cutting head. Muck hoisting may be accomplished by conventional skips.

Shaft boring with a manned downhole machine was first attempted in 1969 by Zeni-McKinney-Williams. In 1980, a 24-ft diameter 670-ft deep shaft was bored and lined in a program sponsored by the U.S. Bureau of Mines. This program involved a full-face shaft borer, followed by a work deck or galloway. A jump form was used to install concrete lining. The shaft boring machine was laser guided and never deviated from true vertical more than 0.75 in. Although the boring machine built a structurally acceptable shaft, progress was insufficient for economic operation. The major problem related to picking the muck off the face and transporting it vertically to a skip loading station.

The first known partial-face machine was built (circa 1965) in Russia, but little information is available about its performance. It was allegedly successful in sinking a 21-ft diameter shaft. A partial-face shaft sinking system capable of 20- to 24-ft diameters has been designed and built by Robbins-Redpath but not utilized as yet. An advantage of a partial-face machine is that access to the face and the head is accomplished more easily than with a full-face unit. A disadvantage is that the partial-face configuration limits the power which can be applied to the rock so that the excavation rate may be less than with full-face equipment.

A shaft boring system has the potential to meet the requirements for shafts in large diameters up to 8,000 ft deep, with accuracy acceptable for high speed hoisting. The capital cost of such a system is less than an equivalent drilling system for shafts larger than about 20 ft in diameter and 1,500 ft deep. All the techniques developed for conventional sinking--such as temporary support, grouting, lining, panning, pumping, and freezing--may be used to control the rock and water inflow. As in conventional sinking, depth limits are largely dictated by hoisting cable capacity.

REAMING

The use of reaming equipment involves drilling a pilot hole and enlarging the hole to finished diameter in one or more additional passes. Both upward and downward reaming are common techniques. In either case, however, rock removal is by gravity and access to the bottom of the shaft is required. The technique is not applicable to the initial access shaft but is generally an economical option for additional shafts once underground works have been extended.

For shafts at smaller diameters (e.g., 12-ft diameter to 3,000 ft deep) or shallower depths (e.g., 1,000 ft deep at 20-ft diameter), raise drilling is commonly used. Where applicable, raise drilling is by far the least expensive method of shaft excavation. However, as with other drilling methods, all the power to the cutting head is transmitted via drill pipe, which limits both the capability and economic feasibility of raise drilling.

Because all raise reaming techniques follow a pilot hole, tolerances of the final shaft are dictated by the accuracy of the pilot hole. Methods to control pilot hole accuracy, as well as the survey tools, are slow and expensive to use and their accuracy levels are not far beyond the required shaft tolerances.

Recently, in South Africa, a sequential reamer was used for larger diameter (i.e., 20-ft) shafts. The raise-type reamer cuts in sequence, first an intermediate diameter and then the final diameter. Although the raise head is full diameter, it is constructed having two independently rotating components. This technique limits the power transmission requirements of the drill string by cutting only a partial face at a given time. The switching between the two components is done automatically.

A down reaming machine, sometimes referred to as a "V" mole, has been used for larger shafts. Like a blind shaft borer, this unit is manned, follows a laser beam, and employs conventional techniques for ground and water control. The principal difference is that rock cuttings are swept down a previously excavated shaft, generally in the 6- to 8-ft diameter range. Because the V-mole power system is located in-hole at the face, much greater power can be applied to the rock. As a result, this type of machine has been used successfully to excavate shafts in hard (to 40,000 psi compressive strength) rock to a diameter of 28 ft. In deeper and larger diameter shafts, capital costs for the equipment required are less than for blind drilling. The extensive power capability of a V-mole has been demonstrated in enlarging a shaft from 8 ft to 24 ft in diameter at a rate exceeding 100 ft per day.

The down reaming method has the potential to meet all shaft excavation requirements to depths of 8,000 ft, provided that access at the bottom to handle muck has already been established.

MECHANICAL IMPACTOR

An impactor shaft sinker has been constructed and tested in the United States, but in one commercial use to date the equipment was not successful in excavating homogeneous, massive rock. Expected advance rates for the impactor are not competitive with rates possible using other types of equipment.

Excavation Methods

Three methods are suggested as options for sinking deep, large-diameter, access shafts. They are pilot hole drilling and reaming, blind boring, and conventional drill-and-blast.

COMBINATION BLIND DRILLING AND REAMING

This method, which is used for initial opening of a mine or other underground workings, is a combination of blind drilling and raise reaming or down reaming. A 6- to 8-ft finished-diameter shaft is blind drilled to final depth and cased with a hydrostatic lining. A smaller diameter unlined pilot hole is also drilled to depth, and a connecting drift is excavated between the two at the working level. Then the pilot hole is enlarged to the required shaft diameter. Muck from the subsequent reaming operation is removed through the blind drilled and lined shaft, which is fitted with a muck hoisting system. Several equipment options are available for enlarging the pilot hole and selection depends on shaft depth and finished diameter:

- single pass reaming with a raise drill
- multiple pass reaming with a raise drill
- raise reaming with a sequential reamer
- down reaming, as with a V-mole (requires either an intermediate raise excavation to about 6-ft diameter or drilling the original pilot hole to at least 2-ft diameter).

Current methods of pilot-hole drilling are expensive and slow, with typical advance rates not exceeding 5 ft per hour. The penetration rate is deliberately kept low to increase accuracy. The accuracy of the pilot hole is important because the final shaft may be fitted with a high speed hoist. Techniques currently used for increasing drilling accuracy create "dog legs" from intermediate deviations and corrections. These "dog legs" also can cause an out-of-specification haulage shaft. Compensation for errors of a few feet in pilot hole alignment can be accomplished using a V-mole type of unit.

At a depth of 3,000 ft, all of the equipment options noted above are feasible. Completing the access shaft with a single pass or sequential reamer extends the state of the art, but the method is within current technological capability.

At 5,000-ft depths, blind drilling of the initial 6- to 8-ft shaft in hard rock is technically marginal. The total weight of the drill string, bit, and weights for pendulum and cutter force exceeds the capacity of any current rig. In addition, accuracy requirements for a drilled hole are difficult, if not impossible, to meet with current technology.

At a depth of 8,000 ft, the procedure of blind drilling the muck hoisting shaft and pilot hole, with subsequent enlargement of the pilot hole to full construction size, is not a practical solution in the near term. Particular problems include drill string and rig availability for the initial blind shaft, pilot hole accuracy, and the effects of squeezing or spalling ground on the preliminary drill, pilot hole, and intermediate or final reaming.

BLIND BORING

Blind shaft boring to full diameter is technically possible, but improvement in performance is required for economic feasibility. The potential exists for favorable advance rates (at least twice as fast as for conventional excavation) because blind shaft borers can apply more power onto the face than drilling methods. Adequate shaft diameters are possible with increased power, and the equipment allows more precise control of deviation than drilling techniques.

A manned shaft boring machine is appropriate for all rock strengths considered and for shaft depths up to 8,000 ft. Any suitable lining system can be employed. Visual inspection and testing of the rock is possible during sinking, and developed techniques for controlling instability or groundwater inflow problems can be applied.

CONVENTIONAL

Drill-and-blast techniques must be considered an option for access shaft excavation and slashing for small-diameter shaft enlargement. Drill-and-blast shafts can be completed very accurately in rock of all strengths considered, and continuous geological inspection is possible so that ground problems can be handled by standard techniques.

Single-pass sinking of full size openings by conventional methods is the only demonstrated means of constructing large-diameter shafts to depths as great as 8,000 ft. The disadvantages of this method include lower advance rates (no more than 10 ft per day can be expected), more disturbed rock mass than with mechanical equipment, labor-intensive construction, and extremely hazardous working conditions.

Research and Development

Shaft sinking by blind shaft boring equipment holds the potential for the shortest schedule and lowest cost of all the methods considered here. Improvements in performance are possible, particularly if additional attention is given to developments in mechanical or pneumatic and vacuum mucking systems.

For drilling and reaming operations, attention should be given to developing the capability for increased accuracy in pilot-hole drilling.

In drilling operations, carbide insert cutters are commonly used. The development of longer-life carbide insert cutters will help to reduce trip time required for cutter replacement. The potential use of new alloy disc cutters should also be investigated for downhole drilling operations. In addition, attention should be devoted to improving cutter bearing seals and developing longer-life bearings. This is particularly important in view of the higher temperatures, debilitating groundwater, and abrasive wear to be expected under adverse conditions in a deep shaft.

For blind shaft boring, a potential future technology involves the development of a submerged boring machine capable not only of applying high horsepower onto the face but also of utilizing an air lift or pumped slurry method of muck removal. A submerged machine could be of great benefit where the hydrostatic pressure of a mud-filled hole is required for shaft stability. However, a major disadvantage would be the need to remove the machine for maintenance and cutter changes. The feasibility of this type of unit may be paced by the development of highly reliable components and longer-life cutters, capable of withstanding heads in excess of 5,000 ft for more than a few hours of operation.

INTERNAL SHAFT EXCAVATION

Types of Equipment

Internal shafts within a deep facility may be temporary or permanent and may be open connections between levels or blind shafts, as the facility design requires. Four types of mechanical equipment can be recommended: raise drills, blind raise drills, blind shaft drills, and multipurpose boring machines.

RAISE DRILLS

The raise drilling operation involves single-pass reaming of pilot holes and requires access to the top and bottom of the shaft. Raise drills have been used for excavation of hard and soft rock, with the largest diameter shafts completed in softer rock.

The equipment has been demonstrated in 20-ft diameter shafts up to 670 ft deep and in 12-ft diameter shafts up to 3,000-ft deep. Using a sequential reamer, 20-ft diameter shafts have been completed to depths greater than 1,000 ft in hard rock. The only limitations to the raise drilling technique are unstable ground (from low strength or exceptional depth) and accuracy as controlled by the pilot-hole drilling.

By a wide margin, raise drills offer the fastest, most economical, and most demonstrated method of construction. Raise drilling with directionally drilled pilot holes will be the optimum method of internal shaft excavation in good ground conditions.

BLIND RAISE (BOX HOLE) DRILLS

Box hole drills are commonly used for the construction of ore passes in stope mines. A pilot hole is not required, and access is necessary only to the bottom of the shaft. Current technology includes equipment with in-the-hole drives and non-rotating drill string, derrick-mounted drives and rotating drill strings, and large-diameter units propelled by pipe-jacking methods. Demonstrated capability of this equipment includes 15-ft diameter shafts to 150-ft lengths and 5-ft diameter shafts to 300-ft lengths. The box hole technique is slower and more labor-intensive than raise drilling. Typical drilling accuracy is about one percent.

BLIND SHAFT DRILLS

The blind shaft drilling operation involves downward drilling without a pilot hole. Access is required only to the top of the shaft; therefore, blind shaft drills can be considered where bottom access is not practical. Although an underground rig does not exist, requirements for development are not extensive. Such a rig would be very similar to a raise drill.

MULTIPURPOSE (FULL-FACE) BORING MACHINE

The multipurpose boring machine (MBM) is a concept under development. As conceived, the MBM is a short, maneuverable machine, similar to a remotely controlled TBM. One such unit is in existence and has undergone laboratory testing. The device has the potential to follow a compound curve, perhaps starting a drift horizontally and then turning vertically to continue excavation. The existing unit--5.7 ft in diameter and equipped with 200 hp of power and variable cutterhead speed--is designed to excavate a 1,000-ft long incline or raise.

Research and Development

To improve the performance of internal shaft excavation equipment, attention should be directed to the following areas:

- Development of an underground blind shaft drill.
- Continued development of the multipurpose boring machine concept.

MUCK HANDLING SYSTEM

Transport in Tunnels

At the heading, muck buckets on the TBM cutterhead scrape muck from the invert and deliver it to a chute at the top of the cutterhead support structure. The chute discharges muck onto a short conveyor which transfers material to the rear of the TBM. The TBM conveyor discharges muck onto a second (trailing) conveyor which is built into a trailing platform and towed behind the TBM.

Movement (haulage) of muck through the tunnel is typically accomplished by one of four types of systems: rail, conveyor, wheeled, or pipeline.

RAIL SYSTEM

A TBM trailing platform is generally fitted with double-track rail and a switch at the end of the platform near the junction with the main tunnel track. Rail-mounted muck cars are filled by one of two methods:

- The discharge point of the trailing conveyor is at a fixed location, to one side of the trailing platform for dual-track platforms. Empty muck cars are transferred from the incoming to the outgoing track with a car-passer, and the cars are positioned under the end of the conveyor for filling. This system can provide continuous muck removal, assuming that a supply of empty cars can be maintained at the heading.
- The trailing conveyor is at least as long as an assembled train and is centrally located with respect to the tunnel walls. Trains remain stationary during muck car filling. The conveyor is fitted with a movable deflector (tripper) which is positioned at locations along the conveyor and can direct muck into cars on one side of the tunnel. After

a train is loaded, muck transfer is halted while the deflector is returned to its starting position at the leading end of the trailing floor for use in loading a train on the opposite side of the tunnel. This system also can provide continuous mucking but generally requires a large trailing platform.

Tunnel haulage is typically on 24- to 36-in. gage rail, with wider gages for larger tunnel diameters. Diesel locomotives are used and, if space is available, tunnel rail may be double tracked. At the mucking shaft, muck cars are emptied with a rotary dump, and muck is transferred into a hoist surge bin.

All facets of the described rail system are state of the art. If grades are relatively flat (less than one percent), this system will provide no-delay haulage for a 5-mile long heading. For unfavorable grades and/or longer hauls, additional ventilation or trolley electric locomotives may be required. The limiting grade for unassisted rail haulage is about three percent (1.7 degrees).

CONVEYOR SYSTEM

Belt conveyors have been used for tunnel haulage on a few TBM projects, but delays associated with belt extension, repair, and maintenance have been significantly greater than for rail systems. In addition, conveyors only haul in one direction. Thus, alternate systems for material and personnel transport must be provided.

A conveyor system of some variety (e.g., pocket, bucket, cover belt) can be used for material transport on any slope, but conventional belt conveyors can be used only for grades up to about 30 to 35 percent (18 to 20 degrees). Heat dissipation and ventilation requirements will be lower for conveyor than for rail systems.

Conveyor systems have the potential to accommodate the increased advance rates anticipated and may be the only equipment capable of maintaining high capacity, uninterrupted service. Recent developments in belt technology and techniques for speedy repair have increased the reliability of conveyor systems and reduced the occurrence of extensive downtime for belt replacement. In many mining and manufacturing operations, belt conveyors have been demonstrated to be the most economical choice for long-distance haulage.

WHEELED SYSTEM

Load-haul-dump (LHD) vehicles will only be useful for very short hauls and for short-term operations such as mobilization. Low profile dump trucks can provide faster, higher capacity service than LHD vehicles, and may be economical for muck haulage in short- to intermediate-length headings. Wheeled systems may be diesel, electric, or battery powered.

Wheeled systems may be preferred where flexibility and maneuverability in tight areas are required, and vehicles can be operated on grades up to about 17 to 20 percent (10 to 11 degrees). However, requirements for flatter inverts and larger openings (i.e., greater than 15 ft) are more stringent than for rail or conveyor haulage.

PIPELINE SYSTEM

Slurry and pneumatic pipelines have been used for bulk material transport. Haulage rates as high as 150 tons per hour of rock have been achieved in special applications. Although capable of continuous, uniform, high-capacity transportation in both horizontal and vertical directions, these systems are not given further attention because the following factors reduce their potential:

- limitations on muck particle sizes
- abrasive wear of pipe, pumps, and valves
- space required near the heading for required plant components
- large power requirements.

Transport in Crosscuts, Intersections, Ramps, and Slopes

For crosscuts and intersections, it is expected that LHD or low-profile trucks could be used for short distance transfer to passing haulage. Loading of the hauling vehicles would be accomplished by mucking shovels or front-end loaders. Extendable conveyors could be used in side passages. However, wheeled vehicles are likely to be preferred for mobility, flexibility, and ease of maintenance.

For ramps and slopes, unassisted rail haulage can be used to handle muck only at grades up to about three percent; conveyor haulage can be used for grades up to about 35 percent (20 degrees). For steeper grades, cars or buckets on track or cable guides can be used if a winch assembly is added to the rear of the boring machine. For dry conditions, upslope excavations with grades greater than about 85 to 100 percent (40 to 45 degrees) will "self-muck" by gravity. With water present, the grade for "self-mucking" is reduced to about 35 percent (20 degrees).

Transport in Shafts

Vertical movement of muck from the bottom of a deep construction shaft can be accomplished by the following methods: conventional hoist, conveyor, pneumatic, and hydraulic.

For conventional hoisting, available equipment includes mechanical friction and drum hoists. This equipment is the only type in common use for vertical movement of material from depths as great as 8,000 ft.

Conveyor systems consisting of bucket elevators and tray-lift conveyors have been used for vertical muck disposal. However, these systems have not been applied in shafts of the depths considered here.

Pneumatic and hydraulic systems have been used for continuous-lift vertical mucking, but not in shafts of the depths considered here. The limitations of this method previously noted for tunnels apply in this case as well.

Research and Development

The most likely methods for horizontal muck transport in long tunnel headings are rail and conveyor haulage. For vertical muck transport in shafts, conventional hoisting equipment is likely to be preferred at this time. Increases in haulage capacity and system reliability can be achieved by implementing equipment developments and extensions of existing technologies, as follows:

- Rail systems that incorporate advances in automation for remote operation, car switching, and dumping would serve adequately for the increased advance rates anticipated.
- Redundant hoisting systems should be considered to allow continuous, reliable mucking for shafts. One system could continue to operate during maintenance (often time consuming) or repairs to the other.
- The potential for use of a vertical conveyor (cover belt) should be investigated for hoisting muck up deep shafts.

In view of the fact that perhaps 20 to 25 percent of all shift time is typically associated with haulage delays and repairs to trailing and backup system components, continuous equipment monitoring techniques should be incorporated to minimize downtime. Redundant systems, which can be automatically utilized as required, should be provided. Remotely operated and robotic systems can be developed for regular maintenance to increase system reliability.

SUMMARY

Mechanical excavation systems are feasible for the construction of deep-underground facilities and the basic technological capabilities exist within the construction industry. Of all the components of a deep facility that are considered here, greatest concern is focused on the excavation of deep, external shafts.

Full-face tunnel boring machines are the preferred method of tunnel excavation. With no-delay haulage and support installation, and incorporation of suggested modifications, an advance rate of 250 to 300 ft per 24-hour day is potentially achievable.

For tunnels at low grade, rail haulage systems should be adequate for muck haulage at the anticipated advance rates. For grades greater than 2 to 3 percent, conveyor haulage will be the preferred method.

Adequate initial support can be installed very near the face on a no-delay basis, provided that the facility is sited in high quality rock. Construction of a final lining can be a decoupled operation, located well behind the trailing floor. A viable system for final lining installation in the immediate vicinity of the TBM is not likely to be developed within the time period under consideration here.

For excavation of crosscuts and short tunnels, recently developed equipment such as the multipurpose boring machine and the mobile miner will be of greatest use. For trimming and shaping operations, roadheaders and water-jet drills will be most effective.

For access shafts, blind shaft boring holds the potential as the quickest, lowest cost sinking method. If attention is given to the development of an improved mucking system, blind shaft boring will be the preferred method. For internal shafts, excavation with raise drill enlargement of directionally drilled pilot holes will be the optimum method.