rt No. FHWA-RD-77-10

EW SENSING SYSTEM FOR PRE-EXCAVATION SUBSURFACE INVESTIGATION FOR TUNNELS IN ROCK MASSES

Vol. I. Feasibility Study and System Design

August 1976
Final Report

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Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D. C. 20590

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Technical Report Documentation Page

1. Report No. FHWA-RD-77-10	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A New Sensing System For Pre-excavation Subsurface Investigation For Tunnels in Rock Masses Volume 1. Feasibility Study and System Design		5. Report Date August 1976
		6. Performing Organization Code
		8. Performing Organization Report No. 1061-TR-3-1
7. Author(s) L.A. Rubin, J.C. Fowler, J.N. Griffin and W.L. Still		
9. Performing Organization Name and Address ENSCO, Inc. 5408A Port Royal Road Springfield, Virginia 22151		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DOT-FH-11-8602
12. Sponsoring Agency Name and Address Offices of Research and Development Federal Highway Administration U.S. Department of Transportation Washington, D.C. 20590		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes FHWA Contract Manager: Charles H. McGogney, HRS-11		

16. Abstract

This report includes a feasibility study and system design for an initial prototype of a sensing system for pre-excavation subsurface investigation for tunnels in rock. Tunnels in rock are very expensive, and costs often rise far above estimates when unforeseen problems are encountered during excavation. New techniques in rapid excavation technology, such as the development of boring machines, have increased the need for improved site investigation. Possibilities for a new sensing system that will provide more complete data on subsurface conditions were investigated. Favorable results obtained from high-resolution geophysical sensing in boreholes have been combined with improvements in drilling of long, horizontal, precise boreholes in order to provide an economical alternative to pilot tunnel for subsurface investigation. Pilot tunnel costs as with all subsurface construction are rising at rates much higher than the economy, thus the use of borehole site investigation has potentially very high benefit/cost characteristics. The prototype system designed is a highly mobile geophysical measurement (data acquisition) system. The system will take electromagnetic radar measurements, pulsed acoustical measurements, and multi-spaced array resistivity measurements. The sensors will be used in traverses along the borehole, and data will be taken and stored on magnetic tape for subsequent reduction and analysis at a computational center. The system could reduce accidents, reduce bid contingencies, and reduce other factors contributing to rapid escalating costs of subsurface excavation. Volume I (FHWA-RD-77-10) describes the feasibility study and system design. Volume II (FHWA-RD-11) is the Appendices A-R.

17. Key Words Site Investigation, Sensing of Geology from Pilot Tunnels and Long Horizontal Boreholes, Pre-excavation Mapping of Tunnels, Ground Probing Radar, Acoustic Sensing in Ground		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 203	22. Price

Form DOT F 1700.7 (8-72)

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PREFACE

The work reported herein was conducted under a Contract with the U.S. Department of Transportation, Federal Highway Administration, Office of Research, Structures and Applied Mechanics Division. This research is a part of FHWA Project 5B2, Tunneling Research Project, Site Investigation Subproject. The authors wish to acknowledge the helpful participation in the effort by Mr. Charles H. McGogney, Contract Manager, along with that of Dr. Donald Linger, Program Coordinator, and his predecessor, Dr. Steven I. Majtenyi. These FHWA staff members, along with several others, provided many technical contributions, guidance, encouragement and much understanding to the ENSCO project staff.

A number of persons and organizations outside of ENSCO contributed to this report. These include Dr. Ronald E. Heuer, University of Illinois; Dr. Eugene L. Foster, UTD Corp; Dr. John C. Cook, The Terradar Company; Dr. George V. Keller, Colorado School of Mines; Dr. Thomas E. Owen, Southwest Research Institute; and Mr. Rexford M. Morey, Geophysical Survey Systems, Inc.

The authors wish to thank the many ENSCO people who contributed in one way or another to this project. We thank especially Edward G. Cunney, Senior Civil Engineer, and Jeffrey A. Bloom, Senior Mechanical Engineer for their valuable inputs to the study and this report. The report could not have been produced without the very-much-appreciated skillful efforts of Raymond L. Farmer, Laura J. Money, Clifford C. Reynolds and Charles F. Taylor.

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1. EXECUTIVE SUMMARY

1.1 INTRODUCTION

This report covers a feasibility study and system design for an initial prototype of a new sensing system for pre-excavation subsurface investigation for tunnels in rock. The work described was performed by ENSCO, Inc. under a Federal Highway Administration (FHWA) contract, during an 18-month period ending in August 1976.

The work reported is part of a DOT coordinated effort by the FHWA Office of Research, Division of Structures and Applied Mechanics, to improve site investigation. It is managed under Project 5B-Tunneling Technology for Future Highways.

Tunnels in rock are very expensive, and costs often rise far above estimates when unforeseen problems are encountered during excavation. Unforeseen problems are encountered frequently because variations in the rock conditions cannot be predicted from surface geology, vertical borings, excavations at tunnel portals, and other available information. Even costly pilot tunnels, excavated along the line of a proposed tunnel, do not provide data that is always representative of rock conditions throughout large tunnel envelopes.

New techniques in rapid excavation technology, such as the development of boring machines, have increased the need for improved site investigation. Changes to meet unforeseen rock conditions cost more when they affect automated equipment than they did when older, slower tunneling techniques were used.

Possibilities for a new sensing system that will provide more complete data on subsurface conditions, and be less expensive than pilot tunnels, have begun to appear recently. Favorable results have been obtained in technology for high-resolution geophysical sensing from boreholes. These results have been combined with improvements in the drilling of long, precise boreholes that are reusable. The work described in this report was planned to exploit the combined technology of high-resolution sensing and precise, reusable boreholes in order to provide an economical alternative to pilot tunnels for subsurface investigations.

The contract objective included specific requirements:

- Conduct a feasibility study of a system for pre-excavation investigation of rock characteristics of significance to tunnel designers and contractors by sensing from long, horizontal boreholes.
- Perform tradeoffs and analyses of sensor candidates which are capable of determining rock characteristics of significance and changes in them within a range of 100 feet (30.5 m).
- Determine that candidate which has the highest benefit/cost ratio, within strict limits for total development cost. The specifics of this requirement were generated within the project and were reviewed and approved by FHWA.
- Perform a detailed design of the resultant prototype system.

The first part of the work (Task A of the contract) was the feasibility study. This study resulted in the specification of a technically feasible "baseline system", the fabrication of which was possible but would have a high risk, be very costly, and provide a system with low initial reliability.

In Task B, Part I, alternative candidates were evaluated to find those which could overcome inadequacies of the baseline system. Task B, Part II included a reassessment of system requirements to admit more favorable alternatives, and it provided specifications for a full-capability "integral system" that became the standard of comparison for later studies.

Task B, Part III of the project involved the determination of minimum requirements for a modular system that would provide only as much data as users could be expected to accept initially, so as to reduce development costs and time. This system would provide needed data with higher initial reliability than the integral system would and could be improved when needed in the future.

Task B, Part IV provided detailed specifications for the modular system design.

1.2 FUNCTIONAL AND TECHNICAL ANALYSES

1.2.1 FUNCTIONAL ANALYSIS

In the functional analysis, the sensing system concept was divided into major subsystems as indicated by heavy outlines in Figure 1. Additional Blocks are shown in Figure 1 for related functions that are not performed by the major subsystems but are essential to the overall operation of the system. Detailed information on the analysis process and considerations is provided in Section 3 of this report.

The subsystem's characteristics are described as follows:

- Downhole Package

  The Downhole Package, as shown conceptually in Figure 2, will have the capability to:

  -- Operate in small diameter boreholes, in all larger boreholes, and in pilot tunnels. Although primarily horizontal, the boreholes may start straight down from the surface, turn to the horizontal, and later climb as much as 45°.

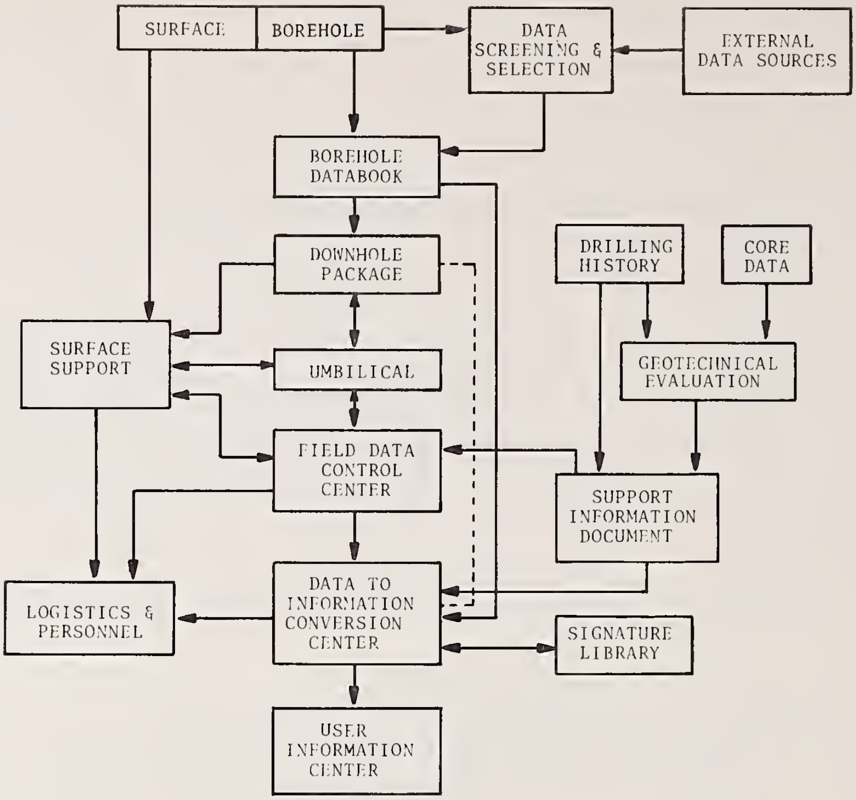


Figure 1. Functional flow between sybsystems.

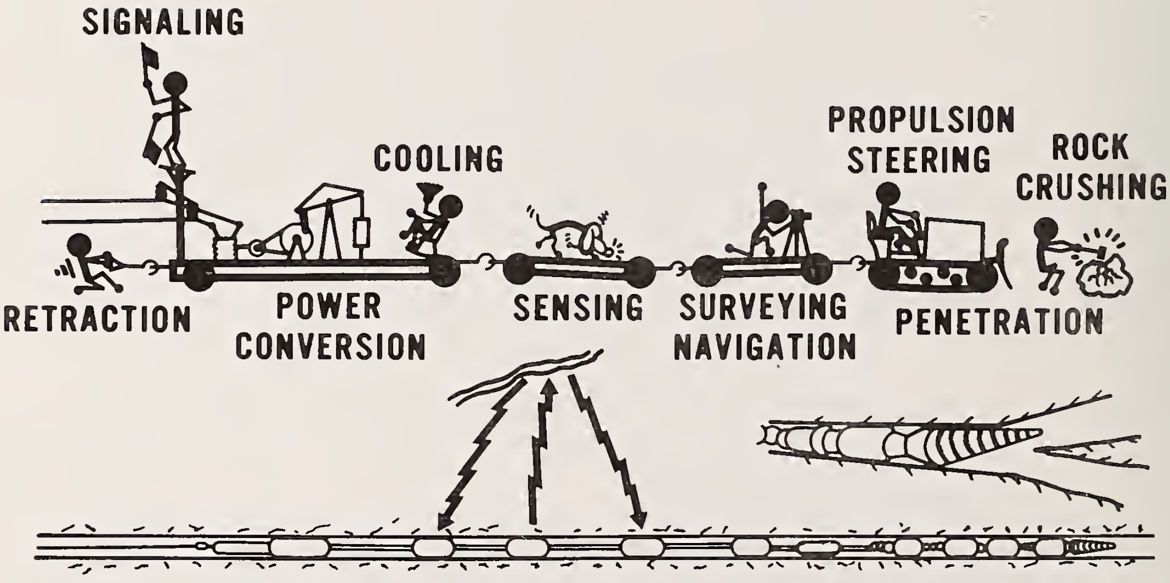


Figure 2. Functions of the downhole package.

- -- Operate in dry, fluid-, or mud-filled holes.
- -- Penetrate minor blockages and debris.
- -- Sense features of geologic, geotechnical, and structural interest with high resolution near the borehole, and sense gross features and constraints to a maximum range of 100 feet (30.5 m).

- Umbilical

  The Umbilical will serve as the single, multifunction connective between the Downhole Package and the Surface Support.

- Surface Support

  The Surface Support will bring to the site everything likely to be needed to do the job and support the human operators.

- Field Data Control Center

  This Center will serve as the central operational point for field test, planning, control, and execution.

- Data-to-Information-Conversion Center

  This Center will process field data off-line, using special purpose signal processing computer programs.

- User Information Center

  This Center will display data tailored to the needs of the civil engineer users.

The borehole data book indicated in Figure 1 will provide information from the driller's log that is needed for the efficient operation of the sensing system.

1.2.2 TECHNICAL ANALYSIS

In the technical feasibility study, available sensing techniques were evaluated and candidates were selected for consideration in the design of the subsurface sensing system. The primary factor in the selection was a capability to sense and locate those rock characteristics that lead to the more frequent and serious problems encountered in tunnel excavations.

The sensor techniques that were evaluated are grouped broadly under electrical, magnetic, electromagnetic, mid-range acoustic, and shock seismic methods. The screening effort narrowed down electrical, magnetic, electromagnetic and acoustic (seismic and mid-range) methods of geophysical exploration to those most applicable to sensing rock characteristics from within a horizontal borehole. Detailed information on the numerous sensing techniques that were considered and on the screening process is provided in Section 4 of this report. Figure 3 provides a guide to the feasibility of probing rock masses with electromagnetic waves.

The methods finally recommended for use in a prototype system are a monocyclic pulse radar, a pulsed acoustic probe, and a multi-electrode resistivity probe. This combination of sensing methods can provide detailed information on rock characteristics close to a borehole and gross information to distances of 100 feet (30.5 m). Use of these three sensing methods was a prime consideration in the development of a "baseline" system concept that could meet all requirements.

1.3 COST AND COST-EFFECTIVENESS ANALYSIS

1.3.1 STUDIES

The first study made covered the costs of boreholes and pilot tunnels. It is described in Appendix P. The average cost of pilot tunnels in the base year 1974 was estimated to range from $225 per foot ($738/m) for easy ground conditions, to $877 per foot ($2777/m) for difficult ground conditions. These costs were for tunnels averaging 2000 feet (609.6 m) in length. Larger pilot tunnels could be expected to have higher unit costs.

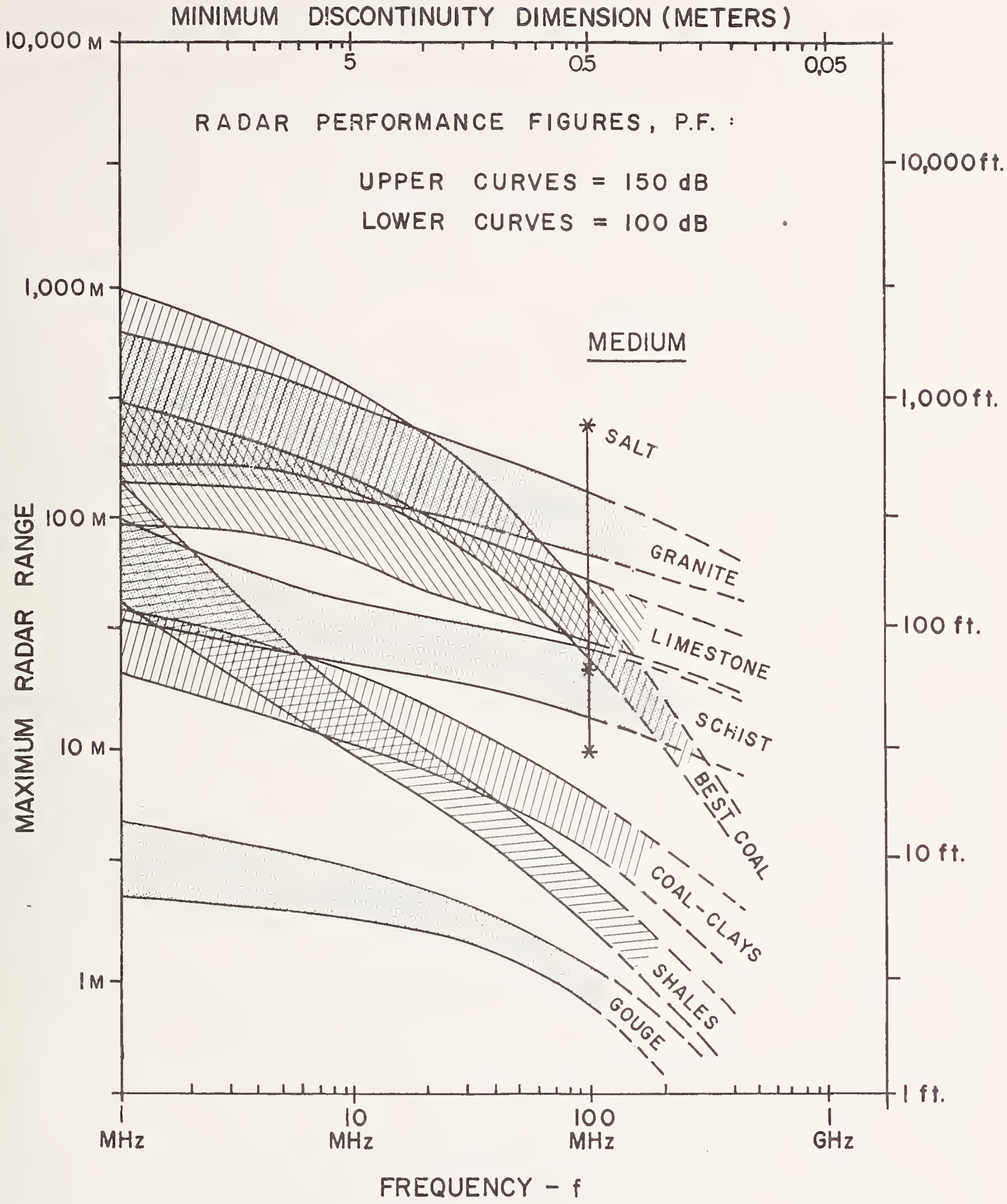


Figure 3. Radar probing distances through some typical " rocks".

Estimates for borehole costs were taken from Table A.18 and Table A.20 of Reference [1] for diamond wire line core drilling. The estimates range from $43.50 per foot ($142.70/m) for a 1000-foot (304.8 m) hole, to $73.10 per foot ($239.70/m) for a 5000-foot (1,524 m) hole. The latter distance is the approximate limit of the state-of-the-art in horizontal drilling. Developments to extend borehole drilling to 10,000 feet (3,048 m) are not expected to increase unit costs but may actually reduce them.

Study of the optimum size for a borehole showed few technical limits. In general, better data can be obtained from larger boreholes up to a size where the borehole is so large that operation of a sensing system which must contact the wall is difficult. Another limiting factor is that large holes will cost more to drill.

The efficiency of coupling energy into rock governs the minimum size of boreholes. For reasonable results, the antennas used should be on the order of one-quarter wavelength. The wavelengths of interest are approximately 42 inches (107 cm) to 21 inches (53 cm). Thus, a six-inch (15 cm) diameter would be a minimum diameter for a borehole radar.

In addition, hydraulic systems and mechanical components for small boreholes are difficult to obtain, and they become very expensive when the boreholes are below three inches (7.6 cm) in diameter.

A related problem is the availability of drilling bits. Diamond drilling is uneconomical except for coring or drilling in hardest rock, and roller cone bits are not available in a wide range for holes below 6-3/4 inches (17 cm).

1.3.2 INTEGRAL (FULL CAPABILITY) SYSTEM

A study was made of the development and operating costs of the integral, full-capability system in order to provide guidelines for selection of cost-effective alternatives in the design of the prototype system. The study is described in detail in Section 6 of this report.

The majority of the components and subsystems of the proposed system will be newly developed items and items that require modifications or repackaging. Therefore, a large amount of subjective judgment based on past experience must be used to obtain cost estimates. A thorough discussion of the estimation procedures is contained in Appendix O.

The total system costs include all identified costs in the development cycle of the system which are estimated as follows:

Phase I	- Feasibility Study and Design	$ 250,000
Phase II	- Prototype Fabrication and Test	$ 650,000
Phase III	- Field Test and Evaluation	$ 150,000
Phase IV	- Fabrication of Operational Model	$ 375,000
	TOTAL	$1,425,000

To these costs were added interest costs over the estimated development time of 60 months, operational costs, contingency costs, and data processing costs, in order to arrive at a total system use cost of $4.28 per foot ($14.44/m). When the cost of the borehole is added, the total is only a fraction of the cost of a pilot tunnel.

Since the estimated development cost for the integral system was more than the funds programmed, and the final system would not be operational until after 60 months, an alternative system was sought which would be less expensive and provide results at an earlier date. This system should have lower developmental risk, and be capable of eventually incorporating all of the functions of the integral system. It was called the modular system.

1.3.3 MODULAR SYSTEM

The modular system will have an initial capability less than the integral system, but its capability will exceed the current needs of the system users. Moreover, it will be designed for the addition of modules for future improvement.

Figures 4 through 6 show conceptual drawings of the configurations of the modular system. Figure 4 shows how the surface support system will be deployed in a typical operation. Figure 5 shows a view that the operator inside the Field Data Conversion Center might have. The control consoles will be arranged so that the operator will be able to view both the outside setup and the control panels easily. Figure 6 shows a conceptual view of the downhole probe in operation.

The detailed characteristics of the modular system are given in Section 7, together with those of the integral system. The modular system will not have a self-propelled borehole package with its own penetrator; the drill rig will furnish propulsion and penetration. The system will be designed so that a propulsion unit can be added at a later date. The acoustic and EM radars will be basically state-of-the-art packages that will limit the azimuthal resolution to approximately 90°. While this is adequate for the foreseeable future, full 5° resolution can be added by acquiring approximately 324 times the data and using synthetic aperature techniques to process the data.

The modular system will be operated with a limited on-site recording capability which will provide real-time monitoring of the data but will not have sophisticated processing capabilities which can be added if needed later.

The changes discussed for the modular system reduced the estimated developmental costs to $887,000 and overall reduced the

Figure 4. Artist's concept of surface support equipment in operation.

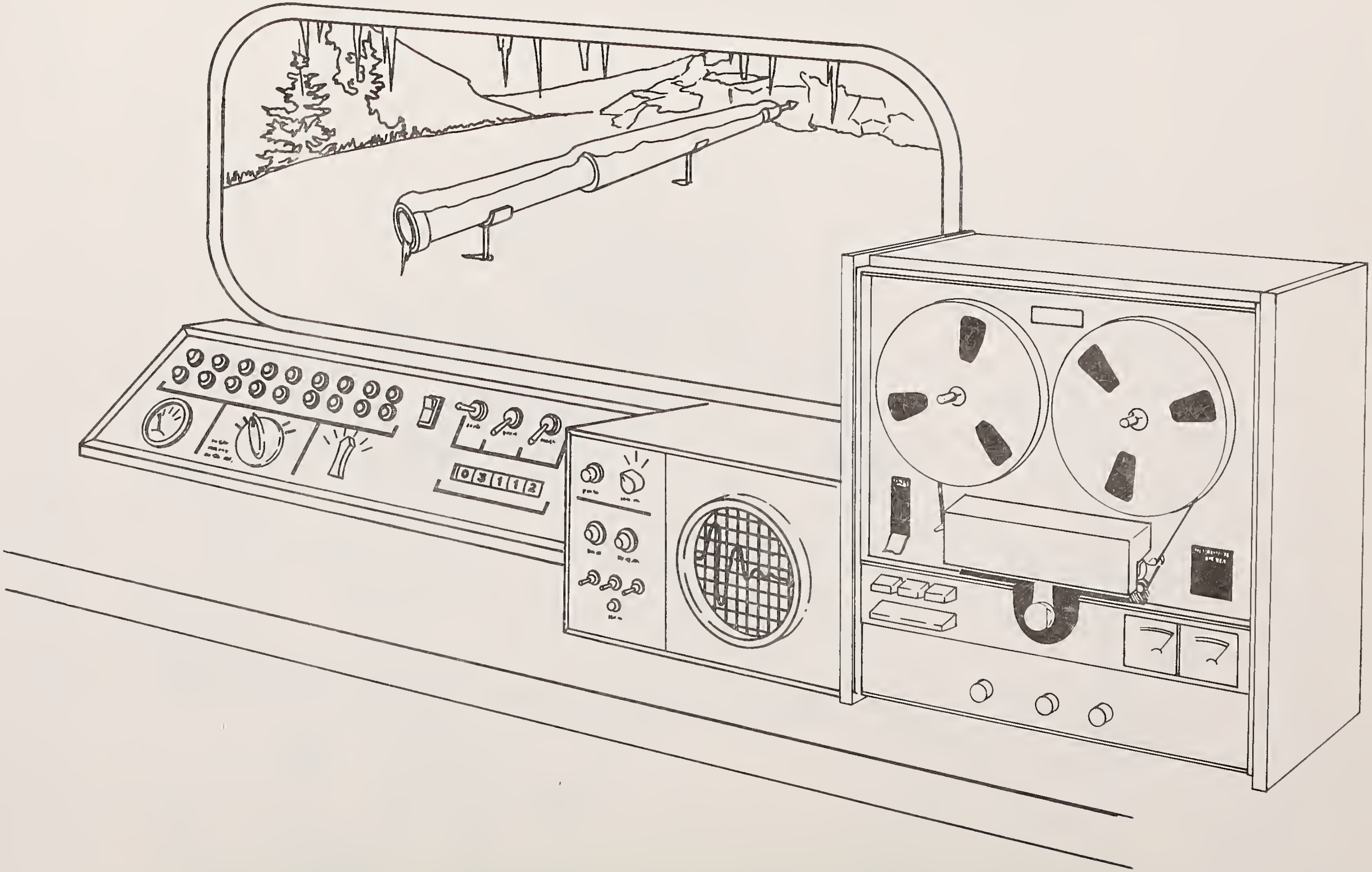


Figure 5. View from inside the control van.

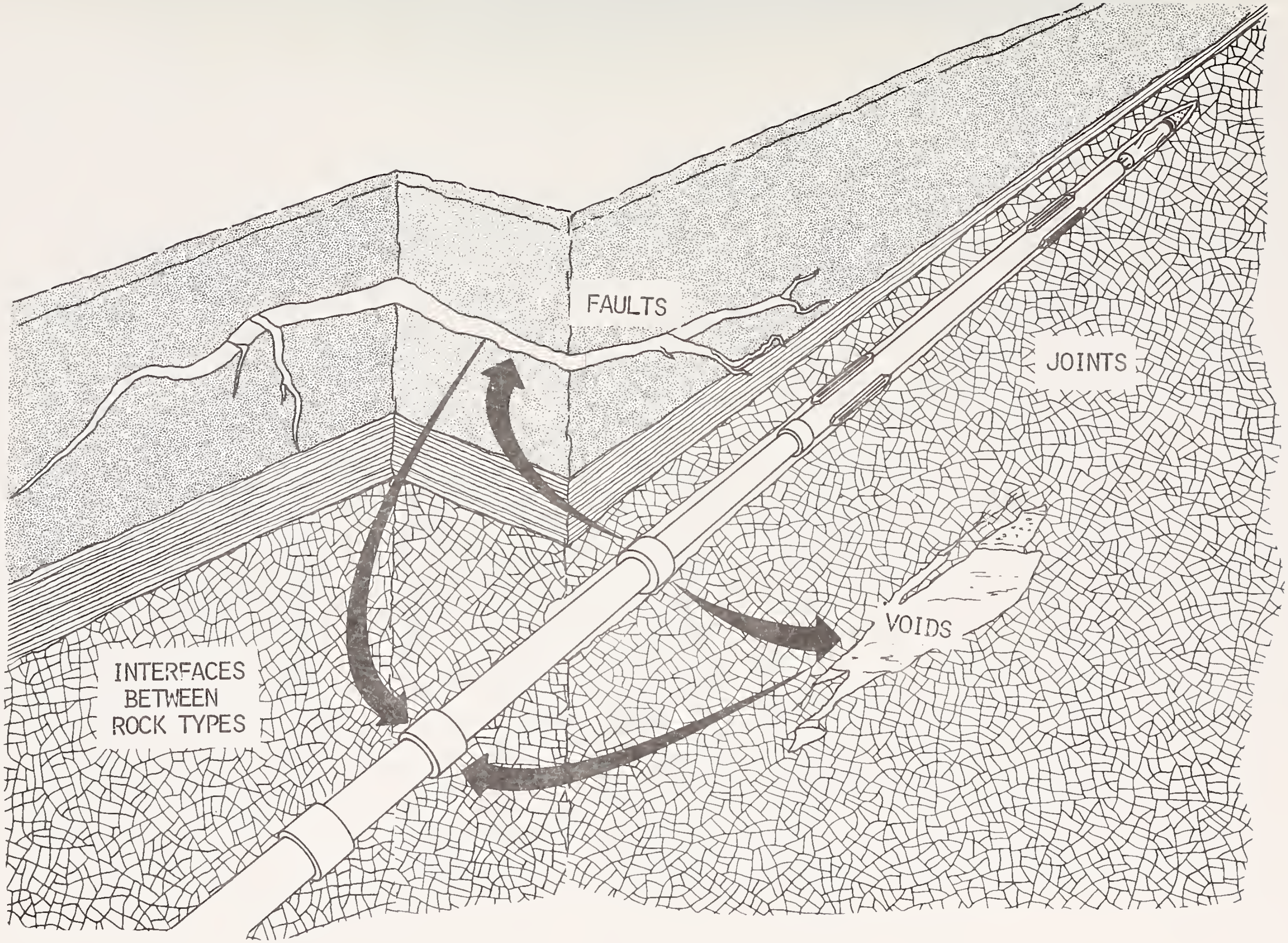


Figure 6. Conceptual view of borehold scenario.

time to 42 months. The total cost of using the system is estimated at \$2.88/ft. (\$8.70/m), including amortization, maintenance, operation, and data processing and interpretation costs.

1.4 RESULTS

1.4.1 PROTOTYPE SYSTEM DESCRIPTION

The prototype system designed is a highly mobile geophysical measurement (data acquisition) system. It is intended to operate primarily in horizontal, pre-drilled boreholes, for hard-rock tunnel site investigation purposes. It must be able to operate off-road under the worst of conditions, arrive at the site, set up rapidly, clean the borehole of minor blockages, and take measurements in the borehole. The functions of major subsystems are described in Section 1.2.1.

The system will take electromagnetic radar measurements, pulsed acoustical measurements, and multi-spaced array resistivity measurements.

The sensors will be used in traverses along the borehole, and data will be taken and stored on magnetic tape for subsequent reduction and analysis at a computational center. Only that data necessary for field decisions on the operations will be displayed and interpreted on site.

The rig that drilled the hole will normally remain on site and may be used to push the downhole package into the hole. After this, the package will be released and the drill rod removed from the hole. A light-duty drill rig may be included as part of the system, for added flexibility and resurvey of the holes when the main drill rig has been removed.

The prototype system design parameters are as follows:

- Hole lengths - to 3,000 feet (914.4 m).
- Hole diameter - 6-3/4, +1/2, -1/8 inch (17 cm, +1.25 cm, -32 mm).
- Hole inclination from vertical - 45° to 135°.
- Resistivity in hole - 1-10,000 ohm-meters, 1000 ohm meters nominal.
- Dielectric constant in hole - 1-80, 9 nominal.
- Hole status

  May be partially blocked with rubble

  May be fluid-filled or dry

  May be deviated several times, with ungrouted rat holes at any azimuthal angle

  May contain voids up to two feet (60 cm) in diameter

  May be a highly abrasive surface equivalent to that of coarse sandpaper.
- Minimum radius of curvature of hole - 500 feet (152 m).
- Hydrostatic head - to 500 psi (3.45 MPa).
- Operating conditions - all-weather, outdoors 24 hours per day.
- Ambient free air temperature - -40°F to 130°F (-40° C to 54.4°C).
- Component temperatures -

  Surface equipment - -40°F to +160°F (-40°C to 71.1°C).

  Downhole equipment - +32°F to +160°F (0°C to 71.1°C).
- Downhole power - 500 watts average.

- Allowable power loss in umbilical cable -

  Long-term average - 10 milliwatts per foot (33 mw/m).

  30-second average - 100 milliwatts per foot (328 mw/m).

- In-hole forces -

  Compressive - 5,000 pounds (2,268 Kg)

  Tensile - 10,000 pounds (4,536 Kg)

- Acceleration along principal axis - ±10g.

- Traverse requirements - 0 to 40 feet (0 to 12 m) per minutes in incremental steps variable from 1 inch (2.5 cm) to 18 (46 cm) inches per step.

- Downhole package lengths -

  Initial - to 35 feet (11 m)

  Growth - to 100 feet (30.5 m) when modules are added to improve capabilities.

  Packages to be assembled in sections of length not to exceed six feet (2 m)

  Nominal package diameter - to 5-1/2 inches (13.97 cm) package must pass over rubble up to 1/2 inch (1.27 cm) gravel.

- Maximum system weight - 10,000 pounds (4,536 Kg) plus three pounds per foot of hole to be surveyed.

1.4.2 SYSTEM SPECIFICATION

To the degree possible, subassemblies within the subsystem are independent and noninteracting. Accordingly, the near state-of-the-art units used initially can be upgraded, one assembly and subsystem at a time, without major system redesigns for each improvement. As specified, the modular system can be developed from the prototype by a series of modest efforts to eventually achieve the full capability planned for the integral system, if operating experience proves this to be cost-effective.

The specifications for the modular system are functional in nature. They specify each subsystem and lower-order to meet the overall system requirements. Since the state-of-the-art and the availability of equipment for the subassemblies are far from uniform, some components will need additional development; other components will require tests to determine which of the available alternatives is most effective. Some components will require packaging studies to insure proper form, fit and function performance within the confines of a borehole. Specifications made in small detail before needed tests and studies are completed could result in the production of system components that are incompatible.

The specifications define the system in sufficient detail for the next logical step in the developmental cycle to take place. They should enable a qualified engineering group to continue the program without repeating work already accomplished and without overlooking opportunities to enhance the effectiveness of the system.

The most serious problem in building a prototype system for sensing from a single borehole, will be achieving adequate angular resolution of signals. There is at present no known satisfactory borehole radiating element with established azimuthal directivity, either acoustic or radar. Working units have been fabricated which indicate that directivity exists, but there is no systematic design approach available and only limited applicable theory. An extended effort is needed, with both theoretical studies and experimental work. Although other problems can be foreseen, they should be resolved satisfactorily by normal advances in the state-of-the-art and by prototype development and test.

1.4.3 SYSTEM PERFORMANCE PROJECTIONS

Under favorable geologic conditions, the modular prototype system has the potential of meeting all the major project goals. Both the acoustic and the radar probes specified will provide penetration and gross resolution to distances in excess of 100 feet (30.5 m). The system will determine the joint patterns and, with proper processing, the joint angles in the rock. Since there are high correlations between acoustic pressure and shear wave velocities, and between electrical resistivities and mechanical properties of rock, rock quality and significant mechanical properties can be determined. Significant changes such as weathering can be detected to 100 feet (30.5 m). Both radar and acoustic probes will provide a capability to detect water-filled cavities, channels, and water-bearing layers, and variations in permeability.

A realistic estimate of the performance under median geologic conditions (e.g., gneiss, schist, etc.) would be system detection ranges initially of 25 to 50 feet (7.5 to 15 m). Thus, system improvement should be considered as an effort to extend the system capability into increasingly difficult environments.

The overall system performance can be expected to improve rapidly as experience is gained by operators and users in the recognition of the signatures of various rock features that show in the signal patterns.

1.5 CONCLUSIONS

The new sensing system for pre-excavation subsurface investigation for tunnels in rock masses will represent great advances in technology. The nearest existing relatives are high-resolution well logs used by energy companies, the surface-profiling radars used to map pipe networks under streets, and the acoustic borehole mapping system used to determine the dip and strike of joint sets in hard rock.

There is already sufficient experimental evidence on such items as behavior of acoustic, electric, and electromagnetic signals in rock masses and anomalies, to warrant high apriori confidence that the results to be obtained from the prototype system will be most favorable. Except for angular resolution of signals, the problems to be solved will generally yield to straightforward engineering approaches insofar as fabrication of the initial prototype is concerned. The very existence and use of the prototype will then be the prime instrument in solving the remaining problems and for the evolutionary development of the system.

The prime determinant in future acceptance and usefulness of this system is the building of an adequate data base of "signatures." These signatures, which in the simplest terms relate remotely sensed rock features to acoustical, electrical, and electromagnetic signal returns, must be collected, proven, dimensioned, categorized, filed, and easily retrieved. Systems of the type represented by the prototype are able only to acquire unrefined data. To be useful, the acquired data must be processed and compared with a library of stored signatures. The geotechnical engineer, once familiar with the process, will have a most powerful tool at his disposal.

There is little doubt that the system, given sufficient signatures, could reduce accidents, bid contingencies, and other factors contributing to rapidly escalating costs of subsurface excavation. One study, performed on a series of actual cases selected at random, indicates that a system of this type could reduce bid contingencies by no less than five percent. This could mean a reduction of $100,000 in the bid contingency cost of $2 million for a one-mile (1.6 Km) average, twenty-million-dollar project. At a hundred dollars per foot (highest estimate), the system costs for data on a one-mile tunnel site would be less than $55,000, and they would provide many other benefits besides reducing contingency costs.

1.6 RECOMMENDATIONS

In view of the rapid development of technology for subsurface investigation, ENSCO recommends careful consideration of all parallel programs. In particular, the mostly unpublicized work in the private sector should be studied. While as many private sector developments as possible have been included in the studies completed, many more will surface in the near future.

An integrated program of signature collection is recommended along with the creation of a central library under a disinterested stewardship, to be supported by all agencies who have a vested interest. Signatures for rock characteristics will be developed under future phases of this and other programs. Without a specific program for standardized acquisition, format, storage, and retrieval, much of this data will be lost or rendered useless.

The effective use by geotechnical personnel of the geological/hydrological data available from the system will require special attention. This is not merely a matter of providing a data display method and format which civil engineers can use and understand. It also requires the early involvement of potential users in programs, so that their viewpoints and inputs can be effective. The eventual modes of data display must be designed with extensive input from the users. The potential users in turn must understand the system and its capabilities in order to provide useful inputs. Thus, ENSCO recommends frequent information exchanges with the geotechnical community, and sponsorship of seminars and workshops.

Finally, because of the critical need to reduce costs in subsurface excavation as an aid to making the use of subsurface space an attractive alternative to surface space in crowded areas, ENSCO urges prompt and timely continuation of this program, at least through the test and evaluation of the prototype system. It is essential to go this far at least, to make the next determination of the benefit/cost of this system.

2. OVERVIEW OF THE PROJECT

2.1 INTRODUCTION TO THE PROJECT

2.1.1 OBJECTIVE

The objective of this project, "A New Sensing System for Pre-Excavation Subsurface Investigation for Tunnels in Rock Masses," was to deliver detailed design documents and theoretical analysis of a complete system for detection, location, and delineation of rock characteristics of significance to tunnel designers and contractors. The systems analyzed were to include (as a basic unit) a self-propelled, guided, retractable device that can penetrate mud-filled, wet or dry, previously-prepared, boreholes or pilot tunnels over distances of about two miles (3.2 km).

The systems analyzed were required to sense, transmit, record, and process a complete set of reliable information:

1. For determining the location of significant discontinuities (gouge zones, cavities) in rock masses within a range of 100 feet (30.5 m) from the axis of the hole.
2. For determining the joint patterns (angles) in the rock.
3. For determining the quality of the rock.
4. For evaluating the significant mechanical properties of the rock and soil materials (identifying materials in the joints and gouge zones).
5. For locating changes in the mechanical properties of the rock mass within the range of 100 feet (30.5 m) and estimate the properties of the materials.
6. For evaluating the hydrogeologic characteristics of the ground including the detection of water-filled cavities, channels and water-bearing layers, and the determination of permeabilities and the level of water table.

7. System cost and cost effectivity studies would be performed for each system considered. The final candidate selected for detailed design drawings and specifications is the system which provides the maximum benefit/cost ratio. The design portion of the work will provide a complete system design for an initial prototype unit to meet the requirements specified for the final candidate system.

2.1.2 TECHNICAL GUIDELINES

The technical guidelines provided at the beginning of the study included:

- The tunnel is deep inside the ground, 1,000 feet (304.8 m) below the ground surface, and has a length of about two miles (3.2 km).
- The environment is rock of any type and in any state or condition. Weathered materials, gouge zones, water-filled cavities, etc., may be present.
- The borehole is unspecified and subject to technical and economical studies.
- The direction of the hole generally is horizontal but may be inclined, curving, or vertical.
- The system should be applicable in dry, wet, or mud-filled holes. Dirt and fragmented rock or soil may plug the hole which shall be eliminated by the device; however, no major driling capabilities are expected from the carriage of the device.
- The information obtained by the system shall be reliable in the approximate range of 100 feet (30.5 m) and major changes in materials shall be indicated by the system in the range of a few hundred feet (100 m).

2.1.3 BACKGROUND

The system desired to be designed and developed in this project represents a substantial advance in existing technology. Approximately seven years ago, an acoustic sensing system of limited capability was developed. This system was an outgrowth of technology developed at Battelle Northwest Laboratories for ultrasonic holographic mapping of materials for non-destructive testing. The group at Battelle sometime later decided to go into the mineral prospecting business and formed a company. One of the early achievements of this group was the finding of a "lost" cased hole which was to be used for de-watering the "Canniken" atomic explosion event at Amchitka. The mineral prospecting system was used quite successfully. The company has now commercialized this capability into a service for finding boreholes for the purposes of intercept boring and for other subsurface applications [2].

During the more active period of the Advanced Research Project Agency (ARPA) Military Geophysics program (circa 1970), several contracts were issued by the Bureau of Mines under its auspices, to study the general problem of acoustic and electromagnetic radar from boreholes and other related areas to aid in rapid-tunneling exploration. The contract number, contractors and abbreviated title of each of these programs are shown in Table 1.

Table 1. ARPA contract list.

Contract Number	Contractor	Title
H0210024	Battelle NW	Two Instrumentation Systems
H0210025*	Honeywell	Excavation Seismology
H0210026	Honeywell	Dielectric Study
H0210032	Bendix	Seismic Holography
H0210033	Bendix	Seismic Determination
H0210037	Jacobs Assoc.	Longhole Drilling
H0210042**	Ohio State U.	EM Pulse Sounding

*Also H0220070

**Also H0230009

These studies indicated early that the objectives of this program could be met, although there seems to have been few specific hardware developments associated with these efforts. The difficulty results from two fundamental and difficult problems which had not at the time been attacked successfully. These two problems are:

- The difficulty of excavating long guided horizontal boreholes, and
- The difficulty of building a library of signatures of sensing signals which can be used easily to identify faults, discontinuities and other geological and hydrogeological anomalies in hard rock from boreholes.

In recent years, other breakthroughs occurred in the electromagnetic exploration of soils near the surface. Two companies, Geophysical Survey Systems, Inc. (GSSI) of Burlington, Massachusetts [3] and the CALSPAN Corporation (formerly Cornell Aeronautical Laboratories of Buffalo, New York), independently developed electromagnetic sensing systems. The GSSI system was built largely with private funding, while the CALSPAN system was built for the U.S. Army for cavity and mine detection. Both systems are now commercialized.

The GSSI system up to 1975 had been used extensively by telephone and electric power companies for mapping the utility networks under streets and busy urban areas [4]. It was successful, and had resolutions to within a few inches and a depth of penetration up to about 10 feet (3.0 m). The CALSPAN System has been used for locating small animal cadavers [5] and for highway pavement work as well as for locating mines.

Other companies had been performing research in electromagnetic and acoustic radar but their work was largely dedicated to obstacle detection rather than deep subsurface mapping of structure. While most of the others possess hardware capable of performing some of this newer work, they neither had reliable field-proven gear nor the necessary signal processing techniques and facilities required to produce the pattern and signature data required in this project. In studying the practical application of both acoustic and electromagnetic radar to subsurface exploration, ENSCO evaluated the potential suppliers of which we were aware.

2.1.4 OTHER PROGRAMS IN SUBSURFACE SITE INVESTIGATION

Other related programs have been started and some completed. These are summarized in Table 2.

This project is unique in that it brings together several well-developed disciplines and utilizes them to further the development of a new family of tools for subsurface investigation and definition of geological conditions in advance of subsurface excavation operations. Another feature is that, because only techiques that are within the present state-of-the-art are to be used, the economic payoff could be almost immediate. It is the unification, systemization, and eventual optimization of these techniques which could provide an important contribution to the determination of geological subsurface structure.

This project stresses meaningful interpretation and correlation of sensor data with existing physically observable geology. Initially, subsurface data will be taken in boreholes of known structure where verified geologic interpretations are available, and any new interpretations can subsequently be verified or refuted by planned future excavation. The actual subsurface sensing data will be gathered by use of reliable hardware components which have demonstrated excellent characteristics.

Table 2

SUMMARY OF PROJECTS IN THE DEVELOPMENT OF SUBSURFACE SITE INVESTIGATION BY REMOTE SENSORS IN BOREHOLES AND TUNNELS

	PROJECT	AGENCY (RFP/CONTRACT)	CONTRACTOR (RFP DUE)	COST $	START	COMPLETE
1.	Improved Acoustic Techniques from Boreholes	FHWA FH-11-8036	Fenix & Scisson	$40K	2/73	8/73 (6)
2.	The Use of Advanced Technologies for Locating Underground Obstacles	DOI 14-01-0001-1570; EPRI 78-20-0	Stanford Research Institute	$85K	5/73	9/74 (7)
3.	Demonstration of Acoustical Survey System	NSF/DOT/FHWA	Holosonics	$40K	2/74	9/74 (8)
4.	Scanned Acoustic Holography for Geologic Prediction	NSF (RANN)	Holosonics	$527K	6/74	12/74 (9)
5.	Soft-Ground Sensing and Penetration	FHWA FH-11-8526	MIT	$98K	7/74	10/75 (10)
6.	Improved Capability for Drilling Long Horizontal Boreholes	FHWA FH-11-8486	Foster-Miller	$200K	7/74	8/75 (11)
7.	System Requirements and Analysis of an Experimental Guided Tunneler	EPRI 7836 ERDA E(49018)-2127	Ingersoll-Rand Research Inc.	$85K	10/74	6/75 (12)
8.	Design of a New Sensing System for Hard-Rock Tunnels	FHWA FH-11-8602	ENSCO	$250K	3/75	9/76
9.	Subsurface Site Investigation by Electromagnetic Radar (Phase I)	NSF (RANN) Grant APR75-13414	ENSCO	$120K	4/75	10/75 (13)
10.	Develop Deep-Penetrating Borehole Geophysical Technique for Predictions of Hazards Ahead of Coal Mining	Bumines Contract No. H0252033	Southwest Res. Institute	$212K	6/75	9/76
11.	Subsurface Site Investigation by Remote Sensors in Boreholes and Tunnels - Phase II	NSF (RANN) Grant APR76-03300	ENSCO	$270K	6/76	7/77
12.	Acoustic Sensing System for Mapping the Soil/Rock Interface and for Detecting and Identifying Objects and Material Changes in Soil Masses Under A Water Table	FHWA FH-11-9120	ENSCO	$540K	8/76	4/78

2.2 TECHNICAL PLAN

2.2.1 TASK A: PROJECT ORGANIZATION AND SYSTEM ANALYSIS

The plan for Task A was to analyze the problems of miniaturization of the sensing device and describe the acoustic, electrical, electromagnetic, magnetic sensing and viewing techniques in rock in light of the objective of this project and the properties of the environment.

The plan also called for performance of a technical and economic feasibility study on the sensing techniques and the dimensions of the sensing system.

Our goal was to define the minimum and optimum diameter holes which are required for obtaining the information specified in the objective. Alternative solutions were to be submitted to the contract manager for evaluation and approval. This phase of the study was to include the following:

1. Theoretical justification of the expected performance.
2. Comparative cost analysis of boring the hole and of excavating a pilot tunnel as a minimum in three different geologic environments.
3. Development and operation cost of the proposed systems.
4. Specifications of the detailed technical performances that are expected from the proposed systems.
5. Description of possible sources of errors, reliability and limitations of the systems.
6. Specific recommendations on a course of action, description and plans for critical laboratory tests, and definition of the success criteria for the laboratory tests.

ENSCO was to study the technical and economical problems of miniaturizing the system, and evaluate acoustic imaging, holographic and wave analyzer techniques in addition to other feasible techniques developed.

Task A covered the preliminary activities of organizing the work and performing the technical and tradeoff analysis of alternative system concepts. The results of Task A were to be a preliminary system design for the optimum sensing system, including a theoretical analysis of the expected performance, specific definitions of success criteria, and recommended critical laboratory tests to be performed in the development stage to provide the experimental data required to meet the specified levels of performance.

2.2.1.1 Subtask A.1--Project Organization and Planning

This subtask consisted mainly of reviewing the Project Plan, personnel assignment and orientation, and data/literature retrieval.

2.2.1.2 Subtask A.2--Problem Analysis

In order to analyze the individual candidate subsystems in a coherent and comparable manner, it was necessary to first define the system requirements through explicit definition of a baseline system. The problem analysis was then essentially an expansion of the system requirements, with special emphasis on the problems of miniaturization of each of the candidate systems and on the interfaces between the sensing, data processing, and display subsystems.

2.2.1.3 Subtask A.3--Feasibility Study of Sensing Techniques

Subtask A.3 was a comprehensive analysis of the various candidate sensing techniques. Economic and performance tradeoffs of each subsystem candidate were accomplished. The various sensing systems examined included acoustic, electrical, electromagnetic, and magnetic. Each sensing system was evaluated in relation to acoustic imaging, holographic, wave analyzer, cross correlation, and other data processing techniques. Each combination was analyzed on the basis of system parameters including sensor size, size and number of boreholes, maintainability, operational costs, accuracy, and reliability. This subtask was critical in determining the geometry of the system, including minimum borehole size and configuration, optimum size of the sensor package and value of sensor information versus cost of sensor.

This subtask was further broken down as follows:

- Technical analysis of sensing techniques
- Cost analysis of boreholes and pilot tunnels
- Cost analysis of sensing systems
- Specifications of candidate systems
- Error, reliability and capability analyses

2.2.1.4 Subtask A.4--Experimental Laboratory Planning

After considerable effort to retrieve data, several suggestions for critical laboratory studies were made. Specific recommendations on a course of action to be executed in Task B were prepared. These included plans for testing, measuring, and correlating rock characteristics at radar frequencies (0.1 to 1 GHz).

2.2.1.5 Subtask A.5--Task A Interim Report with Recommendations

The interim report for Task A included the tradeoffs of alternative sensor systems including analysis of the developmental costs, effectiveness, limitations, probable errors, reliability, borehole requirements, and operating costs of each candidate.

The systems were ranked in accordance with these parameters and on the basis of their abilities to meet the objectives of the research project.

The specifications for a "baseline" system were presented, together with a plan covering the necessary developmental work, laboratory and field tests, definitions of success criteria for each of the tests, and a detailed description of the expected performance characteristics of the completed system including expected limitations and possible sources of errors.

The Task A Activity Network is shown in Figure 7.

2.2.2 TASK B: SYSTEM DESIGN AND CRITICAL LABORATORY TESTS

Upon approval of the plans submitted in the Task A Interim Report, ENSCO was to proceed with the design of the complete system, performing the following:

1. An in-depth analysis of all the theoretical and economical problems of sensing and evaluation. Sources of error were to be analyzed, probable error limits to be described, and plans developed as to the approach intended for use to deal with the anticipated problems during the development of the system.

2. Solutions were to be provided to all problems involved in:

    a. Locating the sensing device in the hole.

    b. Coupling the device with the wall of the hole.

    c. Guiding and displacing the device in the hole.

    d. Communicating the various sensor signals to the ground surface.

    e. Data recording and information processing.

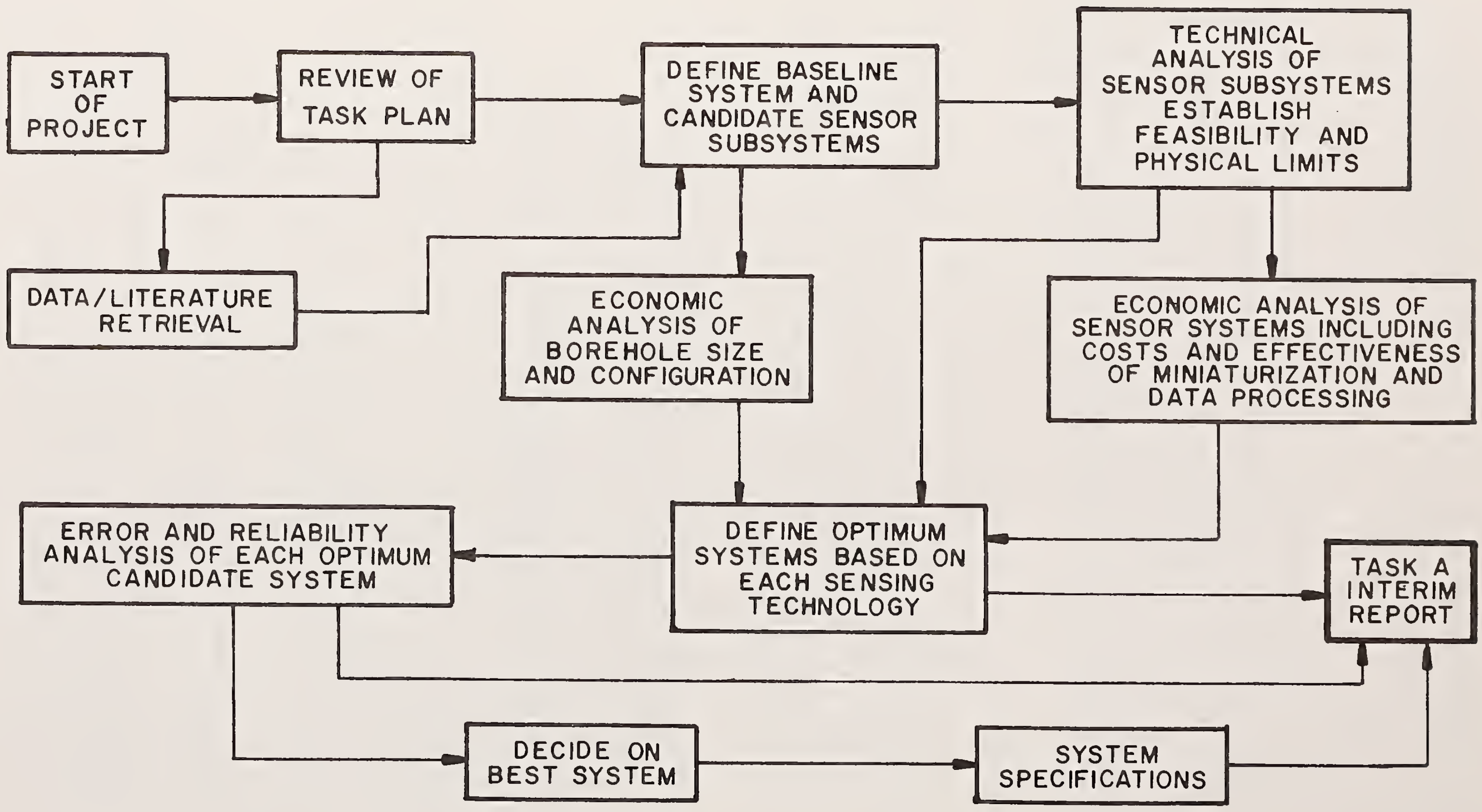


Figure 7. Functional activity network of Task A--Project organization and system analysis.

3. A detailed analysis to be performed of the expectations from the system. This work was to be complete so that the device to be developed could deal with all the possible conditions in the rock environment.

4. The economic analysis performed under Task A was to be updated each time the technical alternatives were presented. Development and service cost estimates, with emphasis on the technical and economic benefits of the alternative solutions (sensitivity or accuracy versus costs of development and costs of operation and service) were to be presented.

5. ENSCO was required to update monthly an activity network diagram for the Federal Highway Administration. In this diagram, the work accomplished, the personnel employed, the future objectives, cost and time estimates of each activity, and possible alternatives were recorded and presented for approval by the contract manager.

6. The critical laboratory tests were to be performed and test results interpreted as planned in Task A.4.

7. The design of the complete subsurface investigation system including the necessary detailed theoretical and economic analysis, drawings, sketches and specifications was to be submitted for approval.

8. The data processing was to satisfy the following conditions:

    a. Be unambiguous

    b. Civil engineers can interpret it.

    c. It can be stored for future reference.

Task B covered the detailed design of the operational field system based on a combination of comprehensive technical and economical analysis and the results from critical laboratory tests. This combined theoretical and empirical approach provided assurances that the final system could be based solidly on existing technology and those critical laboratory tests needed to apply this technology. This interactive design procedure was implemented through the following series of tasks:

2.2.2.1 Subtask B.1--Review and Planning

The task plan included in the Task A Interim Report was revised to include additional guidance from the FHWA.

2.2.2.2 Subtask B.2--Critical Laboratory Tests

The Task A studies identified additional critical experiments to be conducted during Task B. Three areas where critical experiments were needed included:

- Angular resolution of antennas
- Behavior of rocks at radar frequencies
- Coordination of field evaluation of ground-probing radar

2.2.2.3 Subtask B.3--System Analysis and Subsystem Performance Specifications

The individual subsystems initially were to be designed independently. Therefore, to assure that they would operate properly when assembled into the completed package, the performance requirements and interface requirements were to be specified in detail before the detailed design work was started on any of the subsystems. This subtask was a system design effort. The final system is to be designed as a series of black boxes, and all of the relevant parameters can be specified for each box. The system design from this task is used as the formal statement of subsystem criteria by the groups working on the detailed Subsystem Design Subtasks B.4 through B.8.

2.2.2.4 Subtask B.4--Design Specifications for Sensor Subsystem

This subtask covers the design of the complete borehole sensing package, the telemetry, and the field data recording package. Individual components include the power unit, signal generator, transmitting and receiving antennas, sensor location system, downhole data processing, multiplex converter, telemetry and surface data recording devices.

2.2.2.5 Subtask B.5--Design Specifications for Carriage Subsystem

This subtask involved the design and specifications for the mechanical subsystem to convey the sensor subsystem into and out of the borehole.

2.2.2.6 Subtask B.6--Design of Signal Processing Subsystem

The subtask covered the design and specifications of the downstream signal processing. This subsystem takes the data collected in the field from the sensor system and from these data derives the physical characteristics of the underground environment as specified in the section on system objectives.

2.2.2.7 Subtask B.7--Design of Data Display Subsystem

The signal processing subsystem of Subtask B.6 helped define the underground environment. This information must be presented in a way that is readily understandable by civil engineers, and in a format that is storable and easily accessible. Subtask B.7 covered the design of the display to meet these requirements.

2.2.2.8 Subtask B.8--Design of Mobile System Configuration

The various subsystems were designed for optimum performance in their specific operating environments. The system had to be packaged so that it is easily transportable, rugged, and independent of fixed utilities. This subtask concentrated on packaging design of the units required for field operation of this system.

2.2.2.9 Functional Activity Network

The Task B Functional Activity Network is shown in Figure 8.

2.3 CHRONOLOGY OF PROJECT

The first task of the 18-month effort, Task A, covered the feasibility study of the system. This required about four months and culminated in the issuance of an unpublished interim report. The study resulted in the definition of a "baseline" system which was fully capable of meeting all the requirements.

After the feasibility study results were presented to the Federal Highway Administration and the comments were absorbed, concentrated tradeoffs analyses lasting four months were conducted of various sensor candidates and other peripheral systems including: propulsion, data analysis, and up-hole support configurations.

As a result of these tradeoff efforts (Task B, Part II of the project), the baseline system was recosted and found to be essentially too costly and of high developmental risk. At this point in the study, it was determined that this approach, namely the "integral approach", had to be reexamined and traded off against other approaches of less capability but of higher benefit/cost ratio.

In the third portion of the project lasting four months, the emphasis was on finding a system design having the highest benefit/cost ratio independent of capability. However, the system guidelines were that the system must perform at least the minimum capabilities which could be effectively outlined by the geotechnical community today. Thus, it was that the "modular" system was defined having almost the same capability as the integral system but substantially lower cost, lower

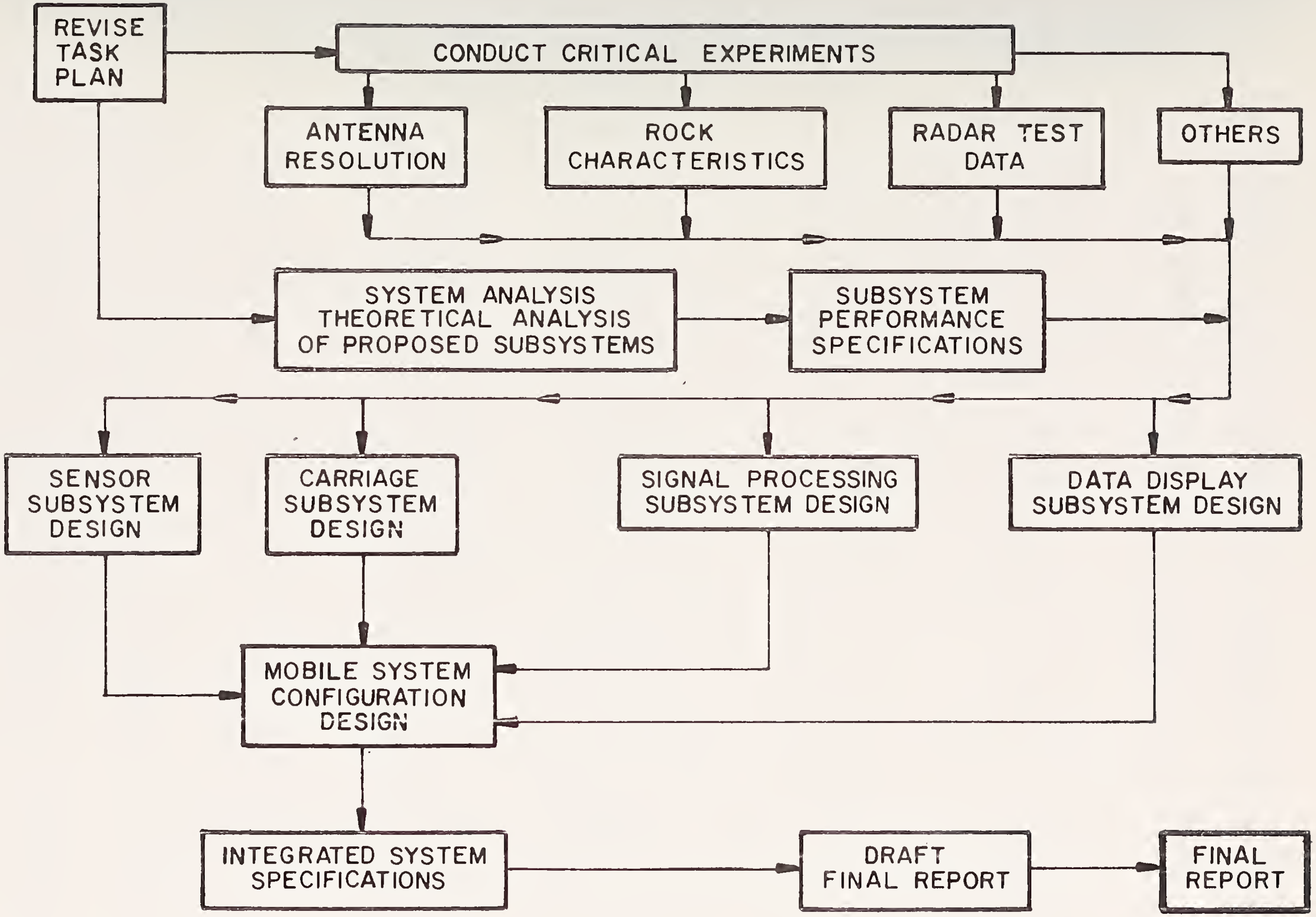


Figure 8. Functional activity network of Task B--system design and critical laboratory tests.

developmental risk and requiring a shorter time to attain operational status.

The final portion (six months) of the project was devoted to the specification and detailed design of the recommended prototype system following selection of the modular system approach. In addition, the final report was prepared.

The chronology followed by ENSCO in pursuing this project was that which could be employed in the time period allocated to achieve the goals. Certain tradeoffs were made during the Task A feasibility study. These are covered in Appendix A. At the end of the Task A study, the baseline system consisted of a reasonably well-defined series of subsystems, all of which were justified on technical and economic bases.

After the Task A study, the tradeoffs were made simply to increase the benefit/cost ratio of the system and not necessarily to improve performance or lead to other operational benefits which might have been pursued.

Again, the emphasis here was to find means of providing a prototype design which was both cost-beneficial and within the projected budgetary constraints of the program, and to be available within the time frame contemplated for the program.

2.4 ORGANIZATION OF REPORT

2.4.1 INTRODUCTION

This final report is organized in two volumes:

- Volume I. Feasibility Study and System Design

- Volume II. Appendices: Detailed Theoretical, Experimental and Economic Foundation

2.4.2 VOLUME I--FEASIBILITY STUDY AND SYSTEM DESIGN

Volume I contains the Executive Summary which was written to provide a brief synopsis of the report. It is written to be comprehensive and a complete report of the studies conducted. Supplementary and supporting documentation is provided in Volume II (Appendices). Volume I is organized to first provide the reader with the background, objectives, and chronology for the system design study (Section 2). This is followed by a functional analysis of the technical requirements (Section 3) which lead to the technical evaluation of the sensor techniques (Section 4). A baseline system configuration was created against which subelements were "tested" for compatibility (Section 5). The cost and cost-benefit studies (Section 6) helps project the total financial commitment to produce the desired system. When this was compared with the risks, cost benefits of a modular system was evident. A prototype system specification (Section 7) is presented, based on revised performance objectives. Recommendations for further development follow the prototype system performance expectations (Section 8). References (Section 9) are included at the end of Volume I.

2.4.3 VOLUME II--APPENDICES: DETAILED THEORETICAL, EXPERIMENTAL, AND ECONOMIC FOUNDATION

In Volume II the 18 appendices are grouped in three parts:

- Part 1. Theoretical Studies
- Part 2. Critical Laboratory Experiments
- Part 3. Economic Considerations.

So that the reader of Volume I does not need all three parts of Volume II available to him to scan the contents, short digests of each appendix follow.

2.4.4 SHORT DIGESTS OF APPENDICES

2.4.4.1 Appendix A, Alternatives Considered for a Feasible Baseline System

In defining the eventual configuration of the system, all major alternatives were considered. This was a continuing process throughout the project. In all, there were three major iterations of the system which occurred.

- The initial baseline system, presented early in the project.
- The integral system presented at the Preliminary Design Review.
- The modular system presented in the specifications defined during this contract.

This appendix is a compilation of the alternatives considered. It starts with a fairly broad screening of the first iteration, in which some specific selections were made and other alternatives left unresolved.

The second iteration starting with paragraph 3 is fairly specific. The selection of the final configuration was based upon pragmatic risk and economic considerations which modified some of the results of the screening. However, all of its features are covered within the alternatives discussed within this document.

2.4.4.2 Appendix B, Rock Characteristics of Significance in Tunneling

The statement of work requires that the new sensing system under this contract deal with "rock characteristics of significance to tunnel designers and contractors."

This appendix was prepared by Dr. Ronald E. Heuer, practicing civil engineer, for ENSCO under a consulting agreement. Additional material was furnished by Mr. Edward Cunney, ENSCO staff civil engineer.

The aim of this work is to bridge the gap between rock anomalies and the physical features which make them "visible" to electrical, acoustic, and electromagnetic sensing signals. The bridge is completed by the next appendix, "Range and Resolution."

It is likely that most readers of this report will not find a need to read this appendix. For those few who are not involved directly in geology or geotechnology, it is recommended reading.

2.4.4.3 Appendix C, Range and Resolution

This continues and completes the overall basis for sensing in hard rock, by relating the characteristic of sensor signals to rock and rock anomalies. It is essential to understand the technique of sensing from boreholes, and should precede the reading of any of the following three appendices. This appendix discusses the relations and trade-offs among detection range, resolution, and wavelength that must be considered in designing acoustic and EM probes. Propagation loss for a variety of rock types is considered. Detection of three configurations of a geologic target is considered: (a) an extensive boundary across which the rock changes character, such as a fault (this is referred to as a "first Fresnel Zone" boundary herein); (b) a localized target within a larger body of rock, such as a small cavity; and (c) a thin but extensive layer within a rock body, such as a clay-filled joint.

2.4.4.4 Appendix D, Acoustic Wave Propagation in Hard Rock

In order to determine the effectiveness of acoustic probing in hard rock, it was first necessary to determine the characteristics of acoustic waves in those rocks of interest.

This appendix starts with the basic physics of wave propagation and ends with curves showing the maximum range for acoustic signals in real rock environments, including the losses associated with the various rock interfaces encountered.

For the reader who is familiar with acoustic wave propagation in near-homogeneous, lossy media, this appendix is not needed. For others, it will be useful in understanding Appendix E.

2.4.4.5 Appendix E, Acoustic Sensing Subsystem Trade-Offs

Once it was decided that the prototype hard-rock sensing system would require an acoustic sensor, a study was conducted to review the state-of-the-art and, by the process of trade-offs, pick the best candidate.

The work reported in this appendix is largely an extension and coverage of the acoustic probe work performed for the U. S. Bureau of Mines and the U.S. Geological Survey by SwRI, and in particular has been extracted from their reports [46] [47]. It is published here by special permission of SwRI and their sponsors--Bureau of Mines (DMRC) and Geological Survey (Denver)--with our thanks.

2.4.4.6 Appendix F, Ground-Probing Radar

The purpose of this Appendix is to introduce the monocyclic pulse radar, list some typical radar parameters, give some recent measurements of electrical properties of various types of rocks, and obtain estimates of the maximum radar range within the various rock types.

2.4.4.7 Appendix G, Electrical Resistivity Probes

The choice of sensor types and sensor ensembles was one of the most critical features of the project. This study analyzes the key features of resistivity probes as potential candidates for the sensor system. It was written early in the project and subsequently updated as the overall system configuration evolved.

2.4.4.8 Appendix H, Signal Processing Techniques Applicable To Subsurface Investigation of Rock Masses Through Boreholes

This study was performed to determine how computerized processing of sensor data can enhance the interpretability of the data.

This appendix covers that topic from a theoretical viewpoint, leading to suggestions of certain processes which seem relevant.

Another appendix (M) makes reference to experimental results carried out on radar sensing data in metamorphic rock.

2.4.4.9 Appendix I, Conceptual Design Study of Hard Rock Sensor Conveyance Device

A major effort of the project was to design a self-propelled conveyance device. This study is one of the documents produced in this effort. The fact that the final system as specified does not include a conveyance such as this does not nullify the value of the work.

The decision not to incorporate a self-propelled thruster in the initial prototype was made on the basis of other factors.

- The state-of-the-art of horizontal drilling is such that it is doubtful that, in the same time frame as the first hardware of this program, there will be holes long enough to need a self-propelled device.
- The sensor concept must first be field proven before a device such as this is needed. Thus, it is possible to separate the development of the thruster from that of the sensor.

2.4.4.10 Appendix J, Applicability of Drill Rigs as Propulsion Devices

This study was based on similar work which was done in examining the problems of horizontal drilling. It was performed late in the program to investigate the probable limits to which a drill rig could be used as a substitute to the in-the-hole thrust generation device which was originally part of the system.

It concludes that the drill rig will be of sufficient utility as a thrust device to make it a desirable replacement for the thruster, but only to relatively shallow penetrations.

2.4.4.11 Appendix K, Investigations of the Physical Properties of the Low-Porosity Rock--A Critical Laboratory Experiment

From the very beginning of this project, the need for more information about the physical properties of low-porosity rock was quite evident.

After the Task A effort was complete and the decision to use acoustics, electromagnetics, and electrical sensors was made, it was apparent that a need to have relevant correlations among the electrical, acoustic, electromagnetic, and strength parameters had to be satisfied.

A contract was negotiated with Colorado School of Mines to conduct this study. The results are included in this appendix. A most significant result for this study is that for these rocks, once the frequency is well above the conductive/dielectric crossover, there appears to be a zone where the attenuation is simply due to the range-dependent spreading loss, and no longer dependent on frequency. The consequence of this is that for borehole-sized antennas (optimum frequencies between 500 MHz and 2 GHz), the radar may be actually more efficient with increasing frequency (see Volume I, Section 4.4.3).

2.4.4.12 Appendix L, Transverse-Dipole Borehole Antennas, A Critical Laboratory Experiment

After the Task A report was published, it became important to investigate the capability of radar antennas to resolve the location of anomalies in planes normal to the borehole.

To this end, Dr. John C. Cook, ENSCO consultant, and ground-probing radar pioneer, performed a study on various antenna configurations. The results of this work are included in this appendix.

2.4.4.13 Appendix M, Subsurface Experiments with Radar

During the conduct of the feasiblity study (Task A) of this project, it was painfully obvious that a number of nagging questions could be best answered by a limited objective field experiment. Since such an experiment would have far-reaching significance to the entire subsurface/excavation community, it was decided to seek more general support. Thus, it was that

ENSCO proposed, and NSF (RANN) supported by a grant, the study entitled, "Subsurface Site Investigation by Electromagnetic Radar--Phase I, Feasibility."

The final report of this project is available from National Technical Information Service at a nominal charge. A short summary is included as this appendix.

2.4.4.14 Appendix N, Comparative Study of Probabilities of Success of Candidate System Design Concepts

At the conclusion of the preliminary system design, it was obvious that any system which attempted to meet the project requirements as stated would have an excessively high developmental risk.

Individually, the developments and advances of the state-of-the-art needed for the system to function were reasonable. However, the cumulative effect of requiring them all to occur together in a total functioning system was such that there was a very low probability of success.

The modular approach was proposed wherein the prototype system would be designed to meet more modest goals, and would also be designed to grow to meet the full capability required.

This paper was written to define in objective terms a condition which was intuitively obvious, but very difficult to present in concise written form.

2.4.4.15 Appendix O, Economic Analysis of Full-Capability System

The contract required that under Task A (Feasibility Study) an economic analysis was to be prepared covering the sensing techniques and dimensions of the sensing device. This study was prepared and included in the Task A report.

Another contract requirement was to update the economic analysis each time technical alternatives were presented. This appendix represents the final alternative candidate presented which would meet the full-capability requirement.

2.4.4.16 Appendix P, Costs of Pilot Tunnels

The original study was completed by Dr. E. L. Foster, Head of the Underground Technology Division of Foster-Miller Associates, Inc., in June 1975. The study was prepared as an appendix to the Task A Report. It was made to provide factual information on costs in support of discussions and conclusions on the merits of boreholes for the collection of data on subsurface materials and their conditions.

The study has been supplemented with information on the costs of pilot tunnels excavated in the metropolitan area of Washington, D.C. Some additional information from Foster-Miller reports prepared for the Federal Highway Administration in October 1975 has also been added in the supplement attached to the study.

2.4.4.17 Appendix Q, Analysis of Sensing Cost-Benefit Ratios as a Function of Borehole Size

A contractual requirement was to determine the most cost-effective minimum borehole diameter for the subsurface sensing system. This study was performed to meet this requirement. It was one of the first contract deliverables but it has been updated several times during the course of the contract as better data has become available.

2.4.4.18 Appendix R, Cost-Effectiveness Considerations for Propulsion and Penetration

One of the decisions defining the final configuration of the system was to eliminate the development of an in-the-hole thrust device for penetration. The concept was to use the drill which produced the borehole to push the survey package. A companion study (Appendix J) indicates that this is a feasible approach, provided the hole length is less than a few thousand feet (1 km).

This short study was performed to examine the relative cost effectivity between using the heavy drill rig which drilled the hole and using a lightweight dedicated drill rig purchased as part of the system.

3. FUNCTIONAL ANALYSIS OF TECHNICAL REQUIREMENT

3.1 INTRODUCTION

Functional analysis is a method of synthesizing a complex system on the basis of a statement of the functions that the system is to accomplish. The process follows the flow chart given in Figure 9. Referring to this figure, the functional requirements are first analyzed for completeness and consistency. New requirements, which are inherent but not stated in the original functional description, are defined and any resulting conflicts resolved. These requirements are then broken into logical groups of related functions based on the existence of clearly definable interfaces or collections of similar functions at a single physical point. These groups become the definable subsystem which collectively will meet all the requirements. The interfaces between these subsystems define the way they must interact to form the system.

There are two classes of interfaces:

- Internal interfaces define the function or data which must be exchanged between subsystems
- External interfaces define those areas where the system must provide/receive information or support to/from elements outside the system.

The structures of subsystems, incorporated by flow lines to indicate the interfaces, becomes the Functional Flow Diagram. This, together with the allocation of requirements between the subsystems, constitutes the first tier of the functional analysis. This can now be reevaluated by various specialty groups for the overall technical impact of the requirements. It should be emphasized that the first tier functional analysis addresses itself to the definition, analysis and allocation of complete

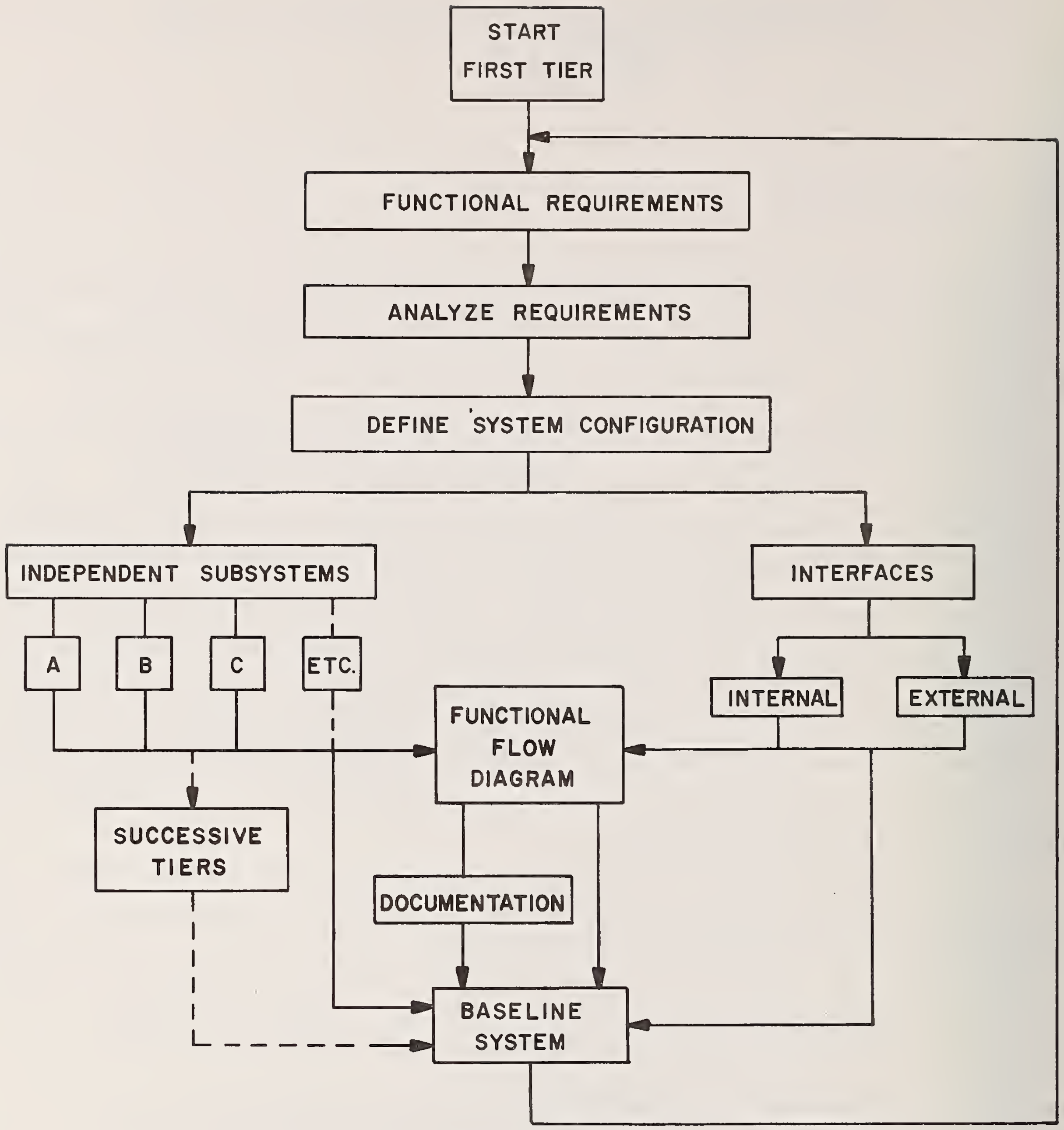


Figure 9. Functional analysis flow diagram.

requirements to subsystems but not to technical solutions to these requirements.

The second tier series of functional analysis consists of a repetition of the first tier approach for each subsystem. However, the internal interfaces of the first tier analysis become the external interfaces of the various subsystems. The second tier analysis addresses itself to technical solutions, and alternative methods of meeting the requirements imposed upon the subsystem and its interfaces.

By the completion of the second tier analysis, a technical solution for meeting all requirements, or an approach to solving the problems involved, has been defined. These are assembled into a "baseline" system which will meet all requirements. In general, the first baseline system will not be intended to function as a system. It provides a preliminary system concept to be refined by subsequent cycles of the analysis.

The functional analysis thus provides a method of evaluating requirements against proposed solutions, and gradually refining the total into a workable system. Following the above approach, the system under development is divided into major subsystems as shown in Figure 10. Functions of these individual subsystems can be briefly described as follows:

The Downhole Package carries the sensing and propulsion equipment into the borehole. The package is connected mechanically as well as electrically by the Umbilical to the Field Data Control Center residing on the surface. The function of the center is to record the data sent to it by the Downhole Package through the Umbilical. This data is then passed on to the Data-to-Information Conversion Center. At this center, the data is converted into information that will be useful and meaningful to the user. This information is then passed on to the User Information Center where the user, based on this data as well

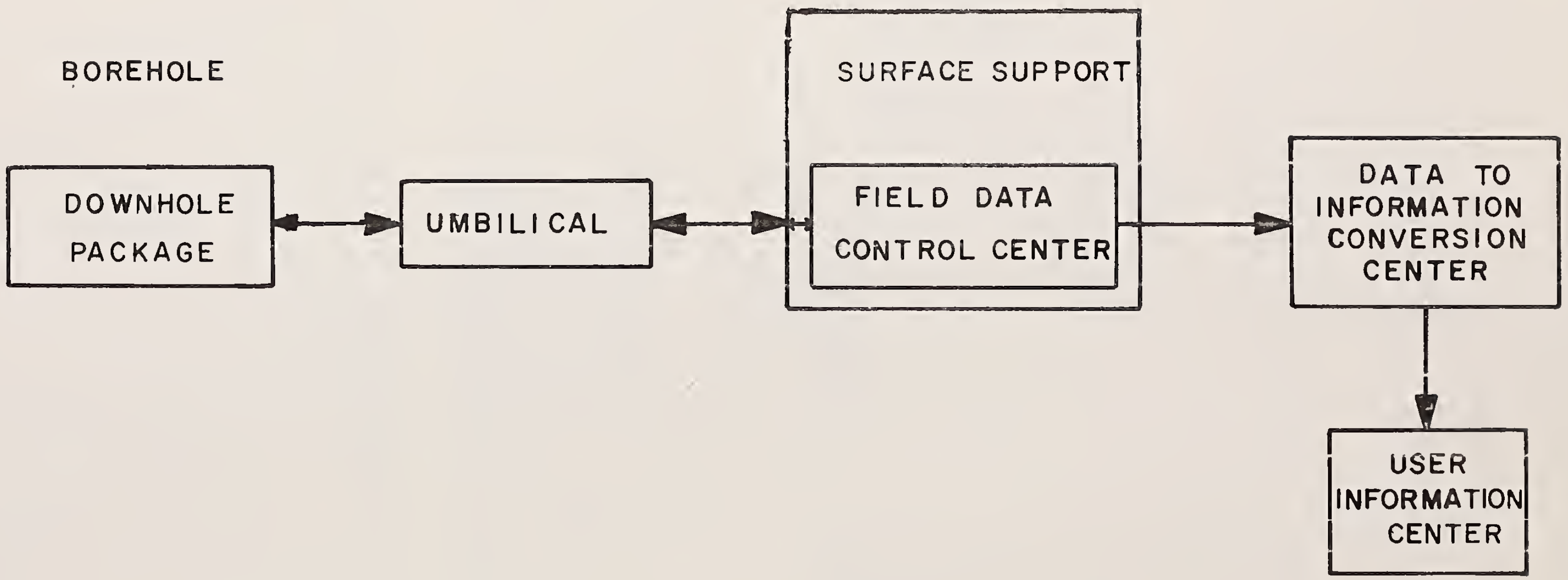


Figure 10. Block-diagrams showing the major subsystems and the direction of information flow between them.

as on previous data and experience, derives the geological structure around the borehole.

Figure 11 shows the first tier functional flow between the major subsystems and interfaces. In addition to the subsystem blocks shown in Figure 11, this figure shows some function blocks that, although not physically tangible like the major subsystems, constitute important functional elements for successful operation of the system. The purpose of inclusion of these blocks in Figure 11 is for aiding the discussion in the following sections.

3.2 SUBSYSTEMS REQUIREMENTS AND ELEMENTS

3.2.1 BOREHOLE DATABOOK

The purpose of the Borehole Databook is to provide a record of information about the borehole that is relevant to the geophysical survey and necessary for efficient carrying out of the survey. It will contain two types of information: specific information about the nature and condition of the hole that is to be surveyed, and general information about propagation in various kinds of rock such as is needed to predict performance and optimum operating parameters in a particular borehole environment. The specific information will be essentially the borehole's drill log: whatever information is available about the length and diameter of the hole; rock types encountered during drilling and their locations; the locations and extents of wash-outs or voids, etc. The general information will include tables or graphs for predicting range and resolution for targets of interest in various kinds of rock and guidelines for selecting the best frequencies and operating parameters for this particular borehole.

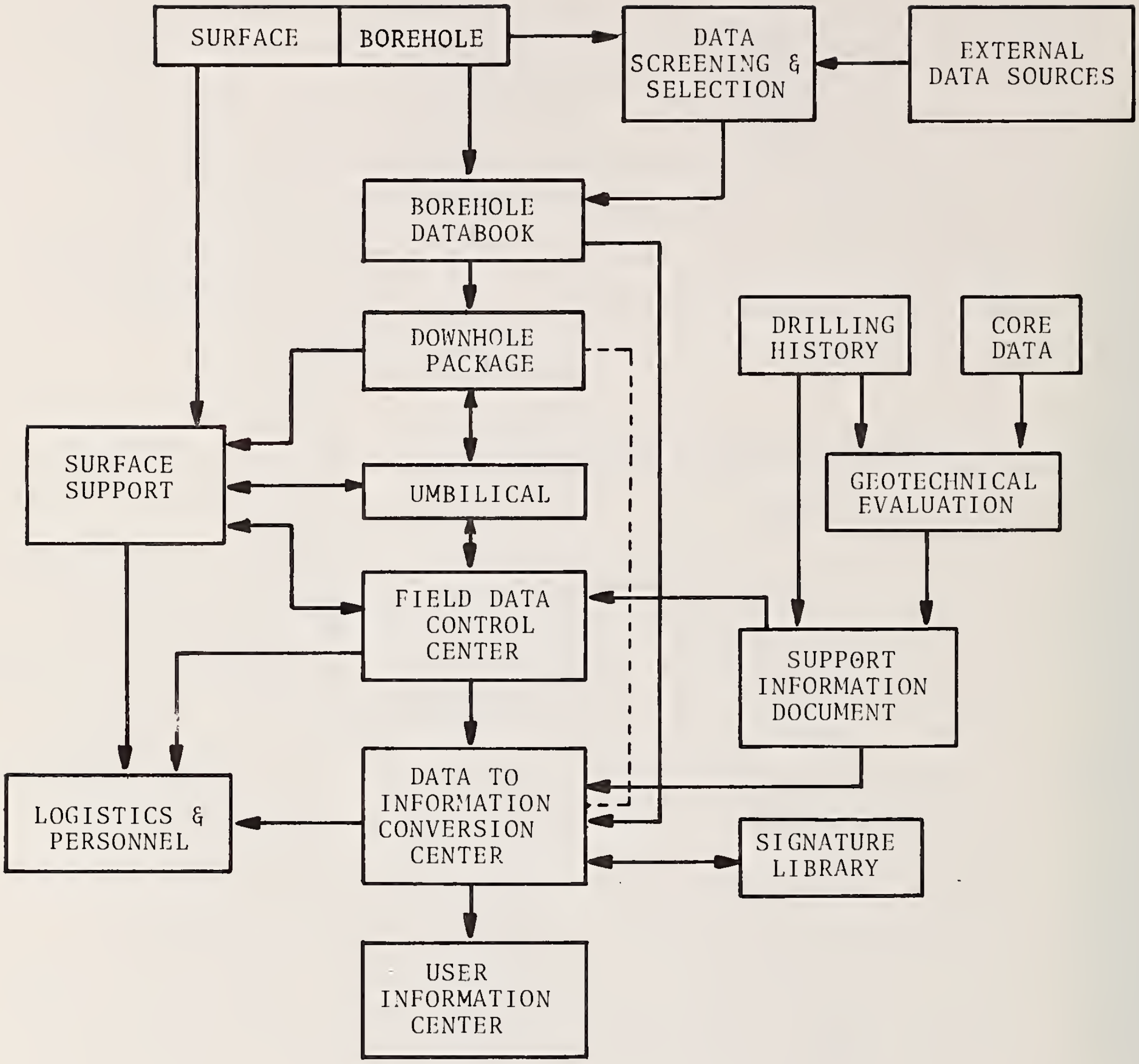


Figure 11. First tier functional flow between major subsystems and interfaces.

3.2.2. DOWNHOLE PACKAGE

In general, the Downhole Package will have the capability to operate in dry, fluid- or mud-filled boreholes, penetrating minor blockages and debris in order to sense features of geologic, geotechnical, and structural interest in the vicinity of the borehole to a range of 100 feet (30.5 m) with high resolution near the borehole. Sensing of only gross features and constraints at maximum range is expected.

Specifically, the downhole package will require:

- A mechanism for emergency recovery of a jammed package.
- A carefully balanced shear-pin system
- An API standard fishing head
- Design to minimize the probability of a jammed package.
- A packaging diameter smaller than the borehole diameter to allow packed mud and minor rock fragments to bypass the package.
- A mechanism to sense and warn of an impenetrable blockage.
- Sufficient thrust to self-propel the package, ultimately to a distance of 10,000 feet (3.0480 km) and provide a limited penetration capability.
- A need for multispeed transfer in the hole. A high speed movement when data is not being taken, and a low-speed precisely controllable mode for measurements.
- Probably a move-stop-measure-move-stop-measure cycle, rather than a continuous helical scan.
- A mechanism of physically coupling acoustic energy with the walls of the borehole.

- Operation in a thermal cooling environment which ranges from very poor for dry holes to excellent for wet holes.
- Operation in the extremely adverse environment from the standpoint of abrasion on physically exposed and moving parts.
- Probable electrical to hydraulic power conversion downhole.
- A maximally quiet environment while readings are being taken. This implies the minimization of electrical and acoustic noise.
- Battery charging capability, battery storage capacity and voltages required for mechanically and electrically quiet operation.
- Hydraulic power and accumulator capability.
- Status sensors and control transducers.
- An information and control subsystem, probably exclusive of and certainly noninterfering with the data transmission subsystem.
- A navigation and orientation subsystem. This must provide vector data on the earth's magnetic field, the orientation of the hole, and the orientation of a package datum line with respect to the local vertical within the hole.
- A flexible physical structure for the package capable of operating around curves or dog-legs in the hole.
- Torsional correlation between vector data and azimuthal sensors.
- A physical interface with the surface support system for transportation, handling, insertion into and removal from the hole.
- Early estimates on weight, diameter, length, and power requirements.

3.2.3 UMBILICAL

There are no explicit requirements for the umbilical subsystem. However, there are a number of inherent and implied requirements which must be considered. The umbilical must:

- Serve as a single, multifunction connection between the Downhole Package and the surface.
- Provide tensile strength up to a specific level.
- Release from the Downhole Package at a specific stress level with adequate safety factor, and be removed from the hole in order not to interfere with subsequent fishing operations.
- Withstand the abrasion caused by in-hole operation.
- Provide the depth measurement function of a navigation subsystem.
- Have predictable stress/strain characteristics, and temperature coefficient, so that by a combination of measurement and calculation its length can be established to an accuracy of better than 1 foot (30 cm).
- Accept electrical power of the order of a few kilowatts, at a specified voltage, transfer through the rotary joint or slip rings of the cable drum, transform it to the optimal voltage for transfer downhole, and deliver it as specified voltage for operation of the downhole package.
- Avoid signal ground loops.
- Minimize crosstalk, electrical and acoustic noise in the cable.
- Provide a single-point grounding system.
- Meet the established power ground requirements.
- Transfer data, navigation, status, and control signals, between its interface with the Downhole Package and its interface with the Field Data Control Center.
- Meet the established logging cable characteristics.

- Be selected from available logging cables if possible. Otherwise, a customized design will be required. This requires early estimates on weight, diameter, length, and power requirements.

3.2.4 SURFACE SUPPORT

Requirements for the surface support subsystem can be inferred from an appraisal of the total mission of the system. These, in general, reduce to one broad requirement: the surface support subsystem must supply all functions necessary for the operation in remote uninhabited areas, not specifically assigned to any other subsystems.

The surface support subsystem must:

- Be mobile and accessible to most tunnel sites.
- Support a crew of at least two men.
- Provide transportation to and from the site for personnel, fuel, and supplies.
- Provide continuous, uninterrupted power, of the proper characteristics.
- Be capable of sustaining operations for not less than one week and possibly up to 30 days.
- Provide at least a minimum level of crew comfort facilities including heating and air conditioning for personnel and equipment.
- Operate over poor road conditions, including freshly bulldozed muddy roads, in inclement weather.
- Provide radio communication with an outside base of support.

- Provide the required logistic support not readily available in the local economy.
- Provide the facilities, tools, and test equipment for assembly, calibration, and maintenance of the other field subsystems.
- Provide the cable drum and draw works for the umbilical subsystem.
- Provide the status and control signals necessary for its operation to the Field Data Control Center.
- Provide space and housekeeping functions to the Field Data Control Center.
- Provide special handling equipment for the downhole package and other accessories when they are removed from the hole.

3.2.5 FIELD DATA CONTROL CENTER (FDCC)

Functional requirements which the Field Data Control Center should meet are the following:

- Serve as a central operational point for field test, planning, control, and execution.
- Make available to the test director information to indicate those points in the tunnel which are expected to provide data of the greatest interest to the eventual user, points in the tunnel where there is danger of blockages or of jamming the tool, points in the hole which can be traversed rapidly and points which may require extremely slow traverses, points in the hole which may require special instrument settings, or specific modes of sensor operation.
- Monitor the status of all critical package subsystems.
- Control of those subsystems within the package for which remote control is a requirement. These include: speed, mode of operation, and direction of motion of the Downhole Package; and draw works for cable retraction.
- Display of the status of all critical subsystems and signals such as the navigational and depth information concerning the package.

- Provide an efficient man/machine interface, in the form of a control console.

- Provide administrative work space for test planning and data storage.

- Perform audio tape recording permit that synchronous with the test data to verbal comment on specific areas of test interest.

- Control and selection of down hole sensing operational modes, gains, and power levels.

- Provide housekeeping and communication equipment.

- Maintain a support information document (the "Borehole Databook") complete with all prior knowledge of the drilling history, available core data, and any geotechnical interpretations deviveed from this data.

The Field Data Control Center is required to have the capability to perform a preliminary data analysis that will enable the field operators to check the reliability of the system and to correct possible errors. Accordingly, the center should provide the following for data processing:

- Recording of the sensor signals from the umbilical in a format suitable both for quick-look display and for subsequent off-line processing in the Data-to-Information Conversion Center.

- A simple visual quick-look data display.

- On-line processing and analysis of the raw data to whatever extent is required to make the quick-look display successful.

- A procedure for interpretation of the quick-look display by the operators to ensure that signals are being transmitted and recorded properly with proper instrument settings.

- Means to enable the operators to correct those errors that can be corrected in the field.

- Recording of the sensor signals from the umbilical in a format suitable both for quick-look display and for subsequent off-line processing in the Data-to-Information Conversion Center.

- Provision for recording physical descriptions of the borehole from cores and driller logs in such a way that they can be correlated later with the signal recordings.

3.2.6 DATA-TO-INFORMATION-CONVERSION CENTER (DICC)

The function of this center is off-line processing of the data that is provided by the FDCC and converting it into the format necessary for effective use at the User Information Center. Examples of what the DICC might be expected to produce are discs or magnetic tapes containing structural information that is in the format needed for plotting and display of geologic profiles, maps, and similar geologic features of special interest. In order to perform this operation, this center should have:

- Computational facility. Most of the functions of the DICC can be provided by any standard computer center of medium capacity of which there are many throughout the country. Time on such a computer center is available for lease at moderate cost.

- Peripheral equipment, e.g. line-printer/plotter/display, on which information such as various structural interfaces or acoustic and electromagnetic impedance contrast profiles can be printed/displayed.

- Computer programs for processing the information. A typical information processing sequence in the DICC is shown in Figure 12. The figure is self-explanatory and is representative of the processing requirements at this center. Examples of the type of processing that can be performed with currently existing special-purpose signal-processing computer programs are given in Appendix H.

- Personnel readily available and competent in the use and operation of the above equipment and of the processing routines.

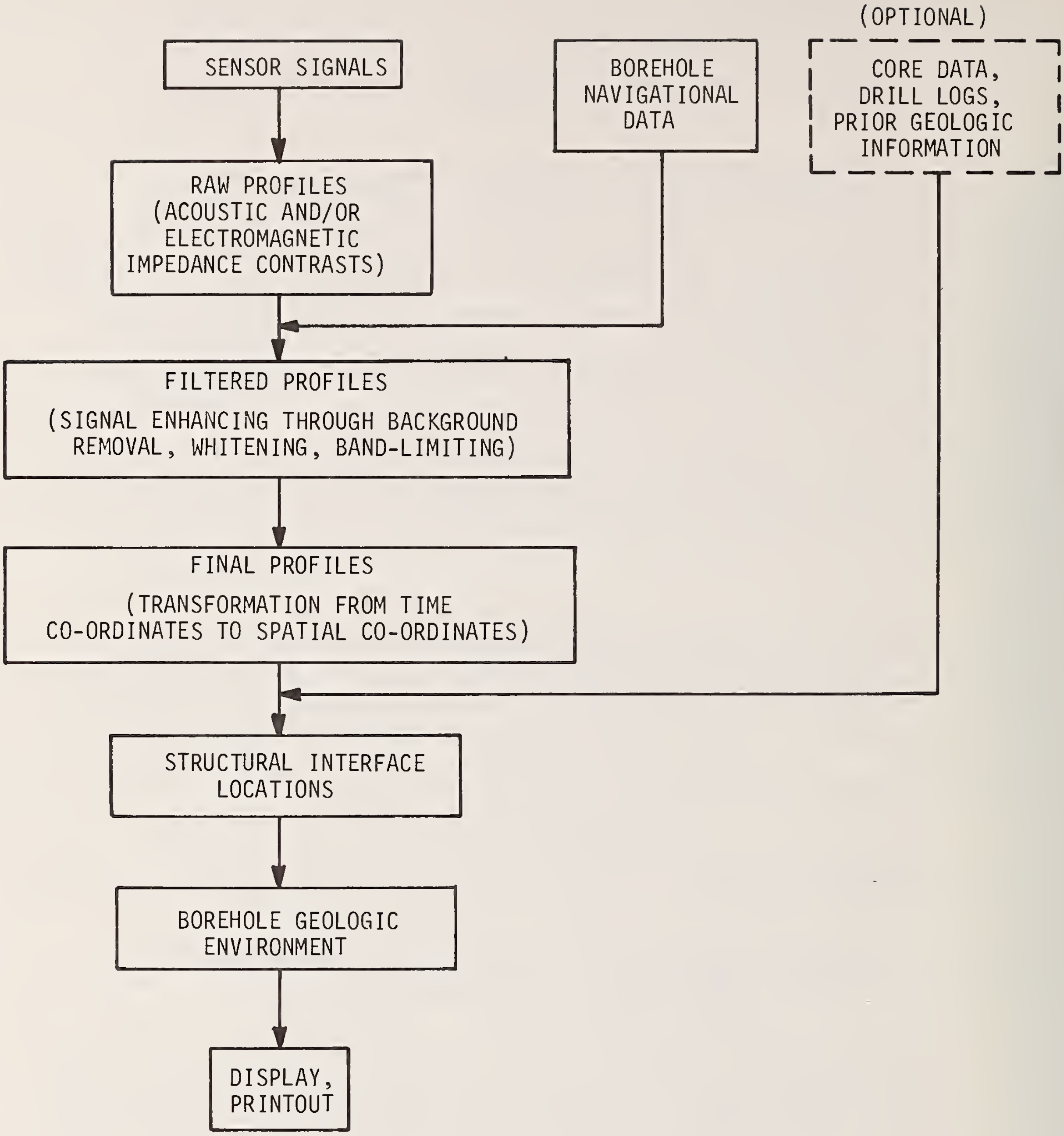


Figure 12. Typical information processing sequence in the Data-to-Information Conversion Center.

Capabilities that would be useful to have at the DICC, although not vital, are the following:

- Access to a reference library of relevant physical parameters such as bulk and shear modulus, density and conductivity, dielectric constant for various earth materials, to supplement the "Borehole Data Book".
- Library of signal signatures for known rock structures.

3.2.7 USER INFORMATION CENTER

This subsystem will provide data summaries, displays and/or models of various kinds. Examples of the kinds of displays that will be important are of the rock mass cross sections at locations of interpreted structural interfaces in planes through the borehole at specified angles of inclination. Transparent overlays and some three-dimensional displays of high-interest targets such as cavities or faults can be important. Photographs or other hard-copy derivatives of such displays will be needed. The end purpose of the displays will be to provide user information in forms that are most useful, such as sections and overlays, isometric drawings, graphs, analog/digital records, histograms, tables, and description comments. The displayed data must:

- Be provided at the least cost at which most of the user requirements can be met effectively.
- Satisfy user requirements on type, degree of significance, quantity or frequency, clarity and format.
- Be compatible with user preferences.
- Be in a form that can be clearly understood by the user.
- Be suitable for easy storage and retrieval.

3.3 INTERFACE REQUIREMENTS AND ELEMENTS

3.3.1 DOWNHOLE PACKAGE TO UMBILICAL

The interface between the Downhole Package and the Umbilical is the major interface between this package and the rest of the system. This interface must provide:

- A suitable mechanism for attaching the cable to the package such that:
  - a) sufficient pull or push can be provided under normal operation, and
  - b) during abnormal conditions, safety against breakage of cable is ensured.

  Shear pins or some form of clutch will be required.
- Adequate electrical line driving and power transformation capability taking into consideration parameters such as voltage, power, regulation, power factor and load impedance.
- Appropriate number of communication or data transfer channels and control signal channels with proper logic voltage levels.
- Multiplexing, if necessary, of the above channels.
- Space for housing all the interface equipment.

3.3.2 DOWNHOLE PACKAGE TO SURFACE SUPPORT

This is not a physical interface but rather a set of general requirements that need to be satisfied on the surface in order to ensure timely, smooth and safe deliver and operation of the downhole package. These requirements are:

- Provision and training of crew in proper use of the equipment.
- Proper design and construction of the vehicle that will carry the equipment and crew. Requirements such as sturdiness for operation in rugged environment, availability of proper power supplies with provision for uninterruptible operation, proper internal environment control for temperature and humidity shall be considered.

- Calibration and maintenance of package
- Assembly and handling of package on surface
- Insertion into and removal from the hole of the package.

3.3.3 UMBILICAL TO SURFACE SUPPORT

The Umbilical to Surface Support interface must consider, coordinate and define:

- The weight, cubage, tensile stress, and retraction speed of the cable.
- The odometer location and mounting.
- The cable control sensors, location and mounting.
- The diameter and the capacity of the cable drum.
- The mechanism for attaching the cable to the drum.
- The signal and energy transfer mechanism (slip rings, rotary joint, etc.)
- Common signal and power grounding requirements to avoid noise and crosstalk on the cables.
- The mounting of the electrical power transformer within the cable drum.
- The connection of signal lines from the slip rings to the Field Data Control Center.

3.3.4 UMBILICAL TO FDCC

The interface between the Umbilical and the FDCC must consider, coordinate, and define:

- The impedance and signal voltages to be transferred.
- The mechanism of transfer.

- The power, space, and location requirements for multiplex, demultiplex and line-driving equipment.
- The specific data input and output requirements.
- Signal ground and common ground requirements.

3.3.5 FDCC TO DICC

The interface between the FDCC and the DICC provides for transfer from the field site of all the signal data and support information needed to describe the borehole environment. This interface could simply consist of a physical transfer of records such as magnetic tapes, drilling logs, and raw profiles from the FDCC to the DICC. Transmission of information over communication lines, leased or owned, is also possible. In the latter case, the process of information transfer will be faster and more direct, but an additional level of error sources and system failure modes will be generated and will have to be investigated. In either case, the following basic requirements must be established and met:

- Compatibility of the output of the signal sensing and navigational recording devices in the FDCC with the input to the converting devices in the DICC, e.g., if a magnetic tape is used, the physical size, recording speed and data format requirements should be compatible between the above devices. To the extent that the compatibility of the information carrier, magtape in the above case, does not exist, this interface should correct for it.
- Timely availability of devices and personnel at both ends for efficient processing and rapid information transfer.
- Transfer of information from physical sources such as core samples, driller's notes, probe operator's logs, etc.

- Feedback to the field operations of critical information that was discovered in the DICC but missed in the FDCC.
- Telephone communication between the two centers.

3.3.6 DICC TO USER INFORMATION CENTER

The interface between the DICC and the UIC must provide for transfer to the user of final, processed information that describes the borehole environment in his choice of terms, and with whatever support information he wants to use in testing and validating his interpretations of the borehole environment.

This interface also could consist simply of a physical transfer of processed data tapes, profiles and other such records from the DICC to the UIC. The possibility of transmitting this information over communication lines also exists with the accompanying risks mentioned previously. The following requirements should be met:

- Compatibility of the output of the processing devices in the DICC with the input to the display devices in the UIC.
- Any hard copy documents provided by the DICC must be in a format easily understood by the user in the UIC.
- Means should be provided for communicating from the UIC back to the DICC so that the user can have control over the type, quality, and quantity of information that he is receiving from the DICC and can also contribute to reference data, such as the "Borehole Data Book", resident in the DICC.

3.3.7 EXTERNAL INTERFACE

There are requirements for information to be delivered to, or received from, sources outside of the control of this system program. These are identified as external interface requirements.

Those external requirements that can be identified include the following:

- Calibration and maintenance procedures for all equipment.
- A support information document that defines everything that will be needed for completed, self-sustained operation without any external support.
- Documentation of the specific types of data which will be needed in the Field Data Control Center.
- Procedures to obtain all key data about the technical characteristics of the borehole.
- Procedures to determine the logistic environment of the local area of the borehole.
- Procedures for pre-planning the survey operation and coordination of these requirements with outside organizations to insure the adequacy and availability of advance data for both the preplanning and measurement phases of the use of this equipment.

4. TECHNICAL EVALUATION OF SENSOR TECHNIQUES

4.1 INTRODUCTION

The technical feasibility of various sensory techniques is discussed in this section. The purpose is to select the more appropriate candidates for further consideration in the design of a subsurface sensory system. The cost factors of the candidates are discussed in Appendices P and Q.

The sensory system is to be used in horizontal boreholes in the conduct of subsurface investigations in rock prior to tunnel excavations. The system objectives and environmental parameters constitute the major trade-off criteria. However, the capability to sense and locate the rock characteristics, or geologic phenomena in general, which lead to the more frequent and serious encounters of unanticipated problems in tunnel excavations, was given the highest priority in the technical evaluation.

To establish this priority, a study was first made to identify the pertinent geologic phenomena and their contribution to unanticipated problems encountered in tunneling. These are discussed in Appendix B.

Selection of the more appropriate candidate sensor techniques to satisfy the requirements is most easily accomplished through review of the capabilities and performance of the various potentially feasible methods of subsurface exploration. Hence, mathematical formulas and detailed technical analysis are minimized in the report body. For completeness, however, reference is made to published works and detailed technical discussions of the selected candidates are given in several appendices.

For discussion purposes, the sensor techniques are broadly grouped under electrical, magnetic, and electromagnetic methods (Section 4.2) and acoustic, seismic, and sonic methods (Section 4.3). Further subdivision of these groups is made as appropriate. There are numerous methods of subsurface prospecting and exploration that are purposefully not discussed. These include specialized techniques for locating ores, mineral deposits, oil, and the like whose presence is not of primary concern in tunneling. The preliminary screening by which the least appropriate techniques were eliminated is summarized in Table 3.

4.2 ELECTRICAL, MAGNETIC AND ELECTROMAGNETIC METHODS

There are several electrical, magnetic, and electromagnetic methods used for geophysical exploration from within boreholes. These can be broadly classified as contacting and non-contacting methods, where the term "contact" refers to whether or not the probes or transducers must be in contact with the medium under investigation. Because the contacting methods are generally used to determine resistivity and operate by driving currents directly through the medium using galvanic contacts, they are often referred to as galvanic resistivity methods. They also fall in the category of electrical methods as opposed to magnetic or electromagnetic because they employ direct current (dc) or, in some cases, a chopped pulsed or slowly varying dc as opposed to natural magnetic effects or electromagnetic radiation.

Non-contacting methods encompass induction, magnetic, and electromagnetic radiation techniques. Induction methods generally employ conducting loops and utilize a time-varying magnetic field at frequencies usually between 100 Hz and 20 kHz. Because the primary energy source is a low-frequency time-varying magnetic field which induces eddy currents in the medium under investigation as opposed to being reflected or

Table 3. Preliminary screening of candidate probe types.

Probe Class	Probe Type	RANGE	RESOLUTION$^{1)}$	AVAILABILITY$^{2)}$	SAFETY	COMPATIBILITY^{3}	INTERPRET-ABILITY$^{4)}$	Notes	Status as Candidate$^{5)}$
Seismic	Pulse-explosive	▨		▨			▨	6)	
	Pulse-mechanical	▨		▨	▨		▨		
	Vibrator	▨		▨	▨	▨			
Acoustic	Pulse-sparker	▨		▨		▨	▨		*
	Pulse-crystal	▨	▨	▨	▨	▨	▨		**
	CW-interferometer	▨		▨	▨	▨			
	CW-holographic	▨	▨		▨		▨		
Electrical	Resistivity	▨	▨	▨	▨	▨			**
	Induced Polariza.	▨		▨	▨	▨		7)	*
	Self-potential	▨		▨	▨	▨			
Electro-magnetic	Pulse	▨	▨	▨	▨	▨	▨		**
	CW	▨		▨	▨	▨			
Magnetic	Needle	▨		▨	▨	▨		8)	
	Fluxgate	▨		▨	▨	▨			
	Proton	▨		▨	▨	▨			
Gravimetric		▨		▨	▨				
Radioactive	Gamma log			▨	▨	▨		9)	
	Neutron log			▨	▨	▨			
Chemical					▨	▨			
Optical				▨	▨	▨			
Mechanical	Strength				▨	▨			
	Permeability	▨		▨	▨				
	Water flow		▨	▨	▨	▨	▨	10)	

NOTES:
▨ Hachured block indicates that probe qualifies in that category.
1) Resolution of hardrock features beyond face of borehole
2) Availability as package that will fit in 6-3/4" borehole
3) Compatibility with traversing operation in borehole
4) Ease & certainty which tunneling hazards can be inferred from data.
5) Double asterisk indicates best choice; not recommended if no asterisk.
6) Includes gas guns, air guns
7) Can be made part of the resistivity package
8) Value in tunneling doubtful; used mostly for detecting metallic minerals
9) Value in tunneling doubtful; in boreholes, use is mostly for detecting hydrocarbons and water
10) Zones of high water flow best logged during drilling of borehole

scattered by the medium, as in general electromagnetic methods, it is often classified as an electrical rather than electromagnetic method. Magnetic methods generally pertain to the passive detection of magnetic materials. They are of little benefit for present purposes, but are briefly discussed below for completeness.

For present purposes, it is advantageous to classify the electrical methods as contacting and induction methods. These are discussed first, followed by magnetic and electromagnetic methods for borehole applications and a brief discussion of general surface and airborne methods.

4.2.1 CONTACT METHODS

The most commonly used methods for measuring resistivity are the contact methods. The basic principle of operation is to establish a current flow between electrodes embedded in or in electrical contact with the medium and measure the resulting currents or potential field. From a knowledge of the electrode configuration, the resistivity can be calculated from the measurements and related to geophysical characteristics. In particular, because of their dependence on porosity, the resistivity and rock strength are correlated (14, 15).

A number of methods for making electrical resistivity measurements, or logging, in oil and water wells have been developed. Because of the obvious potential for adaptation to the subject borehole sensing system, these are reviewed for their feasibility as candidates. These methods, discussed in detail by Keller and Frischknecht (16), include (1) spaced multiple electrode logs, (2) focused current logs, and (3) microspacing logs. Although not a resistivity measuring method, induced polarization logs are discussed as well because they can provide additional data at virtually no additional system cost when used with the contact methods.

4.2.1.1 Spaced Multiple Electrodes

Spaced multiple electrode methods employ a number of fixed-spaced electrodes inside the hole connected to electrodes and measuring instruments at the surface via insulated conductors. Current is driven between one in-hole electrode (usually the deeper one) and an electrode on the surface. A second and often third in-hole measuring electrode is located a short distance back from the driven electrode. If a single measuring electrode is used in conjunction with the driven electrode (forming a "normal" or "potential" array), the resistance measured is that of the medium between the surface return electrode and the equipotential surface of the driven electrode which passes through the measuring electrode.

Greater resolution of the resistivity can be obtained by using two spaced downhole measuring electrodes in conjunction with the driven electrode, as opposed to one (forming a "lateral" or "gradient" array). In this method, the potential between the downhole measuring electrodes is measured. In both methods, the resultant resistivity depends upon the electrode spacings, current, voltage, and the effect of the drilling mud, if present. Drilling mud is generally present and necessary in standard logging operations to ensure good electrical contact. The errors caused by the drilling mud can be substantial. Drilling mud will not necessarily be present during logging in boreholes for tunnel pre-excavation investigations, but alternative techniques for obtaining electrical contact in dry holes have been developed (14). The measurements are also affected by the thickness of resistive zones relative to the in-hole electrode spacings. For example, the normal array does not detect the presence of resistive zones whose thickness is less than the electrode spacing. Such thin layers are detected by the lateral array, unless there are several such nearby layers.

A greater number of in-hole electrodes, spaced at predetermined distances, can be used to measure the resistivity over specified segments to predetermined distances around the borehole. The measured resistivities represent an average value over the bulk of material within the measurement zone of the electrodes. No circumferential or range resolution is obtained. However, spaced electrode methods are commonly employed and accepted, related computerized data processing has been developed, a history of data interpretation in terms of geophysical parameters exists, and the hardware can be readily designed and configured for specific application. It is considered a candidate for one of the sensors of the borehole sensory system, largely to serve as a basic reference system as well as provide meaningful data. The spaced multiple electrode system is discussed further in Appendix A.

4.2.1.2 Focused Current

The focused current logs employ three downhole electrodes, all operating at the same potential, in conjunction with an electrode at the surface. The center in-hole electrode is the main current electrode with the electrodes on either side termed guard electrodes. The guard electrodes focus the current from the center electrode into a disk-shaped area as it flows into the medium around the hole. Beam widths of a few centimeters to 10's of centimeters can be obtained with guard electrode lengths on the order of 4.9 ft (1.5 m). Some error results in measurements of thin layers of resistive materials, but becomes negligible when the thickness is 10 to 20 times the hole diameter. The focused system gives more accurate measurements of resistance than single electrode or spaced electrode methods in the presence of drilling mud. A major disadvantage of the system in general is that the large surface area of the guard electrodes requires a relatively large current, more than can be safely used in some logging operations. However, other types of focused systems have been developed (e.g. Laterolog-7) which employ several point electrodes in an arrangement to essentially serve the function of the guard electrodes and require less current. The Laterolog-7 system is subject to less error for thin layers of resistive material than is the guard band system. It provides accurate measurements in layers as thick as about two times the beam width, or about 2 feet (0.6 meters).

A major advantage of the focused current method in general is that it reduces errors due to the presence of drilling mud. However, drilling mud will not necessarily be present, as mentioned above, in the subject application. Also, proper focus of the current requires uniform electrical contact of the focusing electrodes along the borehole. This is expected to be relatively difficult to maintain simultaneously for several electrodes in a dry borehole. Because there is no apparent advantage of this system in the absence of drilling mud, it is not recommended.

4.2.1.3 Micro-Spacing

Micro-spacing resistivity measurements are made with very short downhole electrode spacings. The electrodes are mounted in pads held against the borehole walls by spring-loaded arms. The electrodes may be spaced in the manner of the normal or lateral array or they may have guard electrodes as in the focused arrays. The micro-spaced logs, as implied by the name, provide a high degree of resolution in measuring thin resistant zones. However, the measurement extends only to about 1 inch (2 or 3 cm) into the rock of the borehole wall. Because of this limited range, it is considered unsuitable for the present application.

4.2.1.4 Induced Polarization

Induced polarization as geophysicists use the term refers to the anomalously large storage of energy which accompanies current flow in most if not all real rocks. The phenomenon is best developed in rocks that contain metal-bearing ores, where the cause is the storage of energy in current-driven chemical reactions such as oxidation and reduction (17). In such rocks, detection of induced polarization comprises a useful prospecting tool.

In rocks with fine-grained silicate minerals, and particularly in those containing clay minerals, somewhat similar chemical reactions take place as ions are stripped from the surfaces of the fine-grained minerals (18, 19). However, the amount of induced polarization is relatively small, and this, combined with the fact that so-called "background" effects in induced polarization are not useful in mineral exploration, has led to this method being largely ignored. What few applications that have been made, though, are of interest in engineering. For example, Baumer et al (20) and Vacquier et al (21) have described moderately successful attempts to locate the ground water table using induced polarization surveys. A much more extensive application of particular interest is that described by Dakhnov et al (22), where many years of induced polarization studies carried out in boreholes indicated that it is possible to estimate the specific internal surface area of a granular rock.

Inclusion of provisions for making induced polarization measurements in a tool which is already equipped to make spaced electric logs is extremely simple. Induced polarization is detected in practice by measuring either the rate of change of electrical resistivity with frequency, or phase of the specific impedance of the ground. Such a system can be extended to make simultaneous determinations of induced polarization by making provisions either for measuring the phase delay of the fundamental of the square wave, or for measuring the relative amplitudes of the fundamental and the first several harmonics of the square wave. The measurements must be done with reasonable accuracy, because phase delays of less than 1° or rates of change of resistivity of less than 0.2% per decade must be detected. Because it can provide additional information at virtually no additional cost, it is considered a candidate member of the sensory package.

4.2.2 INDUCTION METHODS

Induction logging in boreholes employs at least two small coils, or loops, of wire inside the hole with electrical cable connection between these and the out-hole measurement equipment. The coils are generally wound around a long rigid body and oriented coaxially with the borehole. Currents are excited in the medium around the borehole by a time-varying magnetic field generated by one (or more) of the coils.

The frequency of the primary magnetic field is generally 10 to 20 kHz. The primary field induces eddy currents in the medium around the borehole and these currents develop a secondary magnetic field which is measured with a second coil located a few feet from the transmitter coil. The voltage induced in the receiving coil by the secondary field is proportional to the conductivity of the medium and to the square of the frequency. Because of the direct dependence of induced voltage on conductivity, induction logging is generally restricted to use in relatively conductive rocks. Higher frequencies might be used to counter small responses if measurements are needed in resistive rock, but attenuation of the primary field through the medium increases with frequency which also tends to reduce the response. Also, as the frequency is increased, the primary field tends to penetrate conductive bodies less (i.e., skin depth decreases) causing the induction of eddy currents to decrease until at sufficiently high frequencies the response is largely due to surface currents. However, standard induction methods in conductive rock (rock with resistivities less than about 100 ohm-m) provide accurate results. As with the electrical contact methods, the induction methods at present provide no circumferential resolution around the borehole. The induction method does not require contact with the borehole walls nor the presence of drilling mud or water, but will operate in such environments. The frequency may be easily varied during logging, coil orientation could be altered and several coils may be used to shape the primary field. A major restriction on induction systems is that the approximate values of the rock conductivities must be known (within about one order of magnitude) to properly design the system and interpret the results. It is therefore not recommended for the present system over the spaced multiple electrode method.

4.2.3 ELECTROMAGNETIC METHODS

There are a number of potentially useful electromagnetic methods for determining the average electrical properties of the rock around the borehole and one potential electromagnetic method (radar) for accurately locating and mapping geologic discontinuities. Three basic methods that have been employed for measuring average properties are briefly reviewed before discussing the radar methods. These are the two-loop methods, antenna input impedance methods, and axial electric field decay methods discussed by Lytle [23].

4.2.3.1 Two-Loop

This configuration is similar to the induction method, except that the frequency may be much higher (e.g., HF). Also, the mutual impedance between the two loops is the quantity measured rather than secondary fields of eddy currents. The method depends upon loop separation distance, orientation, and the electrical parameters of the surrounding medium. Theoretical calculations of the mutual impedance in terms of the dielectric constant and conductivity of the surrounding medium exist for coaxial and coplaner loops in drill holes. The method has been employed with successful correlations obtained with alternative measurement schemes. This method (using loop antennas) has been shown to be generally impervious to the presence of the hole. It is accurate for measurement of electrical parameters in the immediate vicinity of the borehole. However, interpretation of the results is relatively difficult because of the combined effects of the conductivity and dielectric constant on the results. Also, it is less developed than the electrical contact methods for making geophysical measurements and is not recommended for the present purposes.

4.2.3.2 Antenna Input Impedance

The input impedance of antennas, or wire radiators, is influenced by conducting objects in close proximity to the antenna. This principle has been employed to deduce the electrical properties of borehole mediums using a variety of antenna types such as linear antennas, electrically long insulated antennas, near resonant antennas, and electrically short probes. Such methods are considered accurate for evaluating the conductivity when the dielectric constant can be ignored and vice versa. The range is about one skin depth. At frequencies below about 10 MHz, the skin depth in earth is inversely proportional to the square root of the frequency and conductivity. For example, at 1 MHz, the skin depth may range from about 11.5 ft. (3.5 m) in sandstone to about 55.8 ft. (17 m) in some schists. Also, the sensitivity decreases rapidly with range. For example, the near field of a dipole decreases as the inverse third power of the range. For this reason and because the borehole in the present application may contain mud and fragments which can affect the antenna input impedance and lead to erroneous results, this method is not recommended for present purposes.

4.2.3.3 Axial Electric Field Decay

This method is based on the decay of the electromagnetic field in the axial direction between a transmitting and a receiving antenna inside the borehole. Use of the exponential character of the decay of the signal through the medium allows one to determine the skin depth and conductivity of the medium if the dielectric constant is known. The method is accurate to a range of about one skin depth. Because of the requirement for prior knowledge of the dielectric constant and because a measurement of conductivity is more easily obtained by the spaced-electrode method, this method is not recommended here.

4.2.3.4 Conventional Pulse Radar

In conventional electromagnetic radar, a pulse-modulated continuous wave of radio frequency energy is transmitted. As the pulse propagates through the medium, it is scattered, diffracted, and/or reflected by discontinuities in the constitutive parameters (conductivity and dielectric constant) of the medium. For the present application, such discontinuities will exist at fracture zones, faults, joints, boundaries between different rock masses, water deposits, and in general where nonhomogeneities exist in the medium.

The energy reradiated by the discontinuities is received and analyzed to yield information about the discontinuities. Range from the radar to discontinuity is determined by measurement of the time elapsed between transmission and reception of the pulse, assuming the velocity of propagation is known for the medium. Various characteristics of the received pulse (amplitude, pulse shape, phase, spectral content, etc.) are used to identify characteristics of the discontinuities or targets.

The subsurface environment is a lossy, dispersive, nonhomogeneous medium for propagation of electromagnetic waves. The maximum attainable range in rocks is limited by the propagation losses, or attenuation rate. Also, the attenuation rate in subsurface media increases as the signal frequency increases. This causes a reduction in range resolution with increasing range. The range resolution, or capability to resolve target positions in range and to discriminate between closely spaced targets, is directly related to the radar pulse width. The narrower the pulse, the better the resolution. However, the narrower the pulse, the higher must be the frequency content in the pulse. Thus, as the pulse, which contains a band of frequencies, propagates through the medium, the higher frequency components are attenuated at a higher rate than the lower frequency components. This loss of high frequency content with increasing range results in reduction in the accuracy of measuring the precise time of arrival of the pulse and, hence, reduction of range resolution with increasing range.

The pulse width also dictates the minimum range from which target returns can be received. For a monostatic pulse radar (transmitter and receiver share a common antenna) or bistatic (separate antennas) with the antennas in relatively close proximity, the transmitter must generally be turned off before reception at the transmitted polarization can begin. Otherwise, the receiver responds to the stronger direct transmitted energy. The longer the transmitted pulse duration, the longer the receiver must be off after pulse transmission begins. Hence, the target returns from nearby targets arrive before the receiver is turned on and are therefore not detected.

However, a conventional pulse radar, operating at 230 MHz, has been successfully employed in boreholes for logging in a salt dome [24]. Salt domes, however, are relatively low loss media compared to most subsurface environments and permit propagation to considerable distances. Ranges beyond 984 ft (300 m) were achieved in the borehole logging of the salt dome (24). Their minimum range was limited to 250 ft. (76 meters) to 350 ft. (107 meters), however, by the pulse width. In the present application, the location and discrimination of discontinuities from as near the borehole as possible to ranges of 100 ft. (30.5 meters) or so are of primary importance. The pulse characteristics of the conventional pulse radar used for the borehole logging in the salt dome, or for conventional radar in general, are not suitable for the present application. However, the borehole work done with the conventional pulse radar in the salt dome clearly demonstrated that radar having a peak power of 10 kw into the antenna could be operated in small diameter boreholes [their radar sonde was 5 inches (12.7 cm) in diameter] at in-hole temperatures in excess of 170° F (76.7C) and at pressures on the order of 10,000 psi (68.948 MPa). In principle, a swept frequency pulse, or chirp, technique would permit detection at close range and discrimination between closely spaced discontinuities, and thereby overcome the limitations posed by the conventional radar pulse characteristics. However, it is a more costly and complex technique and has not been as fully developed for subsurface applications as has a monocyclic radar. Therefore, it is not considered a viable alternative at this time to the monocyclic pulse radar discussed next.

4.2.3.5 Monocyclic Pulse Radar

The monocyclic pulse radar, also referred to as subsurface video pulse radar [25], electromagnetic sounder [26], impulse radar [27] and ground-probing radar [28], has been developed during the past decade or so for the express purpose of subsurface investigations. The term monocyclic refers to the fact that the radiated energy is, ideally, a half-cycle of radiofrequency (rf) in the time domain, or a wide spectrum (hence called video) in the frequency domain. This is unlike most conventional pulse radar which, as mentioned above, radiate a pulse containing many cycles of rf. The restriction to a half-cycle (or nearly half-cycle) pulse in the monocyclic pulse radar permits a very short transmitter on-time and hence the receiver can be turned on quickly following the transmission. This permits detection of close-in targets. The short pulse also gives greater range resolution than the conventional pulse radar. Thus, the monocyclic pulse radar circumvents the major disadvantages of the conventional pulse radar in subsurface applications.

Monocyclic pulse radars developed so far typically have pulse widths on the order of nanoseconds, peak powers of watts (although they can be much higher), pulse repetition frequencies of a few hundred hertz, can generally be operated in a monostatic or bistatic mode, and with linear single or crossed polarization [29]. In operation, the received pulses are sampled at successive time intervals and the sampled data used to construct a profile of signal amplitude versus time and/or distance. Time is equivalent to distance (or depth) if the velocity of propagation is known for the medium. Electromagnetic energy is scattered and/or reflected by discontinuities in the propagating medium. The scattering and reflection is dependent upon the incident frequency and the size, shape, orientation, and electrical properties of the discontinuity. Hence, the return signal contains details of the location and characteristics of discontinuities or anomalies in the medium. As with the conventional pulse radar, the resolution in range and target discrimination decreases with increasing distance because the higher frequencies, which are required and inherent in narrow pulses, decay more rapidly with distance in lossy media. However, calculations based on existing monocyclic radar parameters and empirical data indicate that discontinuities should be detectable in limestone to distance of 100 feet (30.5 meters) or so. Further details of the monocyclic radar and its performance characteristics are given in Appendix F.

Monocyclic pulse radar is considered to be a candidate member of the sensory system. The five or six monocyclic radar systems available are considered by their developers to be in a research or prototype form but capable of quantitative measurements with design changes generally required for specific operations [29]. None of the applications, so far, however, have required changes as significant as will be needed for borehole operation. The theory of operation is sufficiently developed to give sound guidelines of expected range in various rock media, but further trade-offs should be studied to see where the major improvement factors are.

4.2.4 MAGNETIC METHODS

Magnetic methods, as generally understood in geophysical applications, are used in the passive detection of naturally occurring magnetic materials. Most rocks contain magnetite. There are other naturally occurring magnetic materials, but magnetite controls the magnetic properties of the vast majority of rocks. Measurements of the magnetic properties of rock, usually done with magnetometers, yield data for distinguishing rock types and are thus useful in delineating the lithology. However, there is no known correlation between magnetite and rock strength, fractures, faults, gouge zones or similar discontinuities of significance in tunneling [30]. Boundaries between different types of rock masses are significant in tunneling, but lithology is not one of the more urgent areas in which improved data and data interpretation are needed for tunnel excavations. Hence, the use of magnetic sensors is not recommended at present for the subject application.

4.2.5 GENERAL SURFACE AND AIRBORNE METHODS OF SUBSURFACE EXPLORATION

There are several electrical and electromagnetic methods used in subsurface exploration which do not require the source and/or receiver to be inside the borehole. However they are not particularly well suited for the subject borehole application. The purpose here is to identify and dismiss these from further consideration.

Based largely on the requirements for identification and location of discontinuities and anomalies in the immediate vicinity [100 ft. (30.5 m) radius] of the borehole beneath a deep overburden [possibly 1000 ft. (305 m) or more], electrical or electromagnetic methods that require conduction or propagation through the overburden are dismissed. These include such methods as airborne type surveys, utilization of existing electromagnetic radiation from radio broadcast stations, utilization of the natural variations in the earth's electromagnetic field (magneto-telluric and telluric methods), surface-to-hole, and surface-to-surface methods. In essence, this includes all methods which do not have both the energy source and receiver within the borehole (with the possible exception of a system terminal near the borehole entrance or in an adjacent borehole). The exclusion of this general class of methods from this particular application is not intended as a general rejection of such methods in subsurface exploration for other purposes. For example, electromagnetic surface-to-borehole measurements are useful is estimating the electrical properties of the medium between the surface and borehole.

For present purposes, however, a knowledge of the environment in the vicinity of the borehole is the more urgent requirement and the methods that require conduction or propagation through the overburden are not considered further because they:

(1) encompass a much larger environment (overburden) than necessary, which tends to average or deemphasize any local anomalies,

(2) are largely nonrepresentative of the environment below the borehole, and

(3) may be relatively nonresponsive to small but significant geological features because the wavelengths (for propagation) would necessarily be larger in order to propagate through the overburden than would be required for systems confined to the borehole and required to propagate over short distances.

4.3 ACOUSTIC AND SEISMIC METHODS

Some discussion on the usage of the terms "acoustic", "seismic", and "sonic" in subsurface applications seems in order before proceeding to a discussion on the better approach for the subject borehole application.

The term "acoustics" is a noun which is defined as "the branch of physics that deals with sound or sound waves" [31]. Every acoustic phenomenon involves the vibration of particles of a medium, moving back and forth under the combination of stiffness and inertial forces. Viewed in this broad sense, the field of acoustics deals with mechanical waves at all frequencies in all substances [32]. As the frequency of sound increases, however, the wavelength becomes smaller and will ultimately approach the dimension of the atomic or molecular structure of the medium. A sound wave in the usual sense is not supported by a medium of discrete particles spaced widely compared to the wavelength. There is thus an upper limit to the frequency of sound waves. This limit is about 10^9 Hz in gases and 10^{14} Hz in liquids and solids, with the practical limit being three or more orders of magnitude less [32]. There is no such lower limit. Frequencies of fractions of hertz are used in earthquake studies and the lower limit may practically be assumed to approach zero.

Within the broad field of acoustics, other terms are commonly used to indicate a narrowing of interest or to refer to specific applications. In fact, in a narrow sense, acoustic waves have been defined to have their frequencies "limited to the range from about 20 Hz to 15 kHz, which produces the auditory sensation of sound for the average person," while in the "broader sense they also include the ultrasonic frequencies above 15 kHz." [33]

The term "seismic" is an often-used adjective in the field of acoustics that is defined as "pertaining to, of the nature of, or caused by an earthquake." [31] The term seismic appears to be most commonly used to describe elastic waves in the earth that are below the audible frequency range. The term "sonics" is a noun defined as "the branch of science that deals with the practical applications of sound." [31] "Ultrasonic" is an adjective "noting or pertaining to a frequency above the audio-frequency range." [31]

The terms acoustic wave, mechanical wave, elastic wave, and sonic wave appear to be used somewhat interchangeably in practice [32 through 36]. In short, there seems to be considerable overlap in the terminology used in the literature with the choice of terms dictated by the author's interpretation as to the more descriptive of his work. In the practical applications of sound waves to investigate subsurface rock characteristics, we choose here to refer to the signals as acoustic (in or above the audio range) and seismic (below the audio range). Attention is now turned to selecting an appropriate acoustic method of the subject borehole application.

4.3.1 GENERAL SURFACE METHODS OF SUBSURFACE EXPLORATION USING ACOUSTICS

There are several methods used in subsurface exploration which do not require the acoustic source and/or receiver to be inside a borehole. As in similar electrical and electromagnetic methods, they are not particularly well suited for the subject borehole application. The purpose here is to identify and dismiss these from further consideration.

Based largely on the requirement for identification and location of discontinuities and anomalies in the immediate vicinity [100 ft. (30.5 m) radius] of the borehole beneath a deep overburden [possibly 1000 ft. (or 305 m) or more], acoustic methods that require propagation through the overburden are dismissed. These include such methods as utilization of naturally occurring acoustic fields (such as in the studies of seismic disturbances), surface-to-surface and surface-to-hole methods. In essence, this includes all methods which do not have both the energy source and receiver within the borehole. The exclusion of this general class of acoustic methods from this particular application is not intended as a rejection of such methods in subsurface exploration for other purposes.

For present purposes, however, a knowledge of the environment in the vicinity of the borehole is the more urgent requirement. Hence, acoustic methods that require propagation through the overburden are not considered further because they:

(1) encompass a much larger environment (overburden) than necessary which tends to average or deemphasize any local anomalies,

(2) are largely nonrepresentative of the environment below the borehole, and

(3) may be relatively nonresponsive to small but significant geological features because in order to propagate through the overburden, the wavelengths would necessarily be larger than would be required for systems confined to the borehole and required to propagate over short distances.

4.3.2 ACOUSTIC METHODS IN BOREHOLE LOGGING

Acoustic devices have been used in standard borehole logging operations for several years. Various types are in use. A brief review of some of these will serve to illustrate the degree of miniaturization of existing downhole acoustic systems and suggest the feasibility of acoustic techniques for borehole application.

4.3.2.1 Borehole Compensated (BHC) Sonic Logging System

An acoustic velocity logging system for borehole application was introduced commercially by the Seismograph Service Corporation in 1951. The system, developed by the Mobile Oil Company, was called a Continuous Velocity Logging (CVL) device [37]. The in-hole tool of the initial CVL consisted of one acoustic transmitter and one receiver mounted at a fixed longitudinal spacing on a small-diameter structural support. The parameter measured was the travel time of an acoustic wave from the transmitter to receiver. Variations of the travel time with in-hole travel of the tool were used to deduce, primarily, the porosity of the hole boundary. The single receiver device was later modified to a two-receiver tool principally to eliminate undesirable effects on velocity measurements caused by the mud in caved areas of the hole [38]. The device was still subject to large errors caused by variations in the hole diameter, lack of tool centering and tilting of the tool in the hole. This made interpretations difficult, particularly in the vicinity of thin beds. A new logging system was later developed to compensate for these effects.

This device, called the Bore Hole Compensated (BHC) Sonic logging system, uses one transmitter above and one transmitter below two pairs of sonic receivers [39]. The effect of hole-size changes on the upper half of the array, consisting of a transmitter and two receivers, is in opposite direction to the effect on the lower half. The average transit time measurements from the two halves of the array automatically cancel the error. Errors caused by a tilt of the sonde axis (i.e., sonde not aligned parallel to hole axis) are also substantially eliminated. BHC logs are commonly run with a three foot (0.9 m) spacing between each transmitter and its nearest receiver and with a two foot (0.6 m) spacing between the receivers [39]. The transducers are acoustically isolated by means of rubber insulators which contain mechanically damped stress members.

The sonde is centered in the hole by multiple centralizers that work against the hole boundaries. The transmitting transducers are magnetostriction types and transmit pulses of 17 to 25 microseconds in width at a rate of 20 times per second.

The receiving transducers operate on the piezoelectric principle. The device operates in fluid-filled holes. The acoustic energy is coupled between the transducers and the borehole walls via the fluid, or mud. The detected signals resulting from a transmitted pulse are amplified and transmitted via cable, along with a synchronizing pulse, to the surface recording equipment. Digital circuitry is employed in the system to maintain stable operation and obtain precise timing measurements. The system is flexible in that combinations among the transmitters and receivers may be employed to effectively change array spacing. The BHC sonic logs have been used to determine porosity, to detect fracture zones, for correlation with other logs, for lithologic determination, and as an aid in geophysical interpretation. Its zone of coverage, or range, is essentially confined to the immediate vicinity of the borehole. Because of the range limitation, it is not a candidate for the subject system.

4.3.2.2 Three-Dimension (3-D) Velocity Log

A modified acoustic logging system called the "3-D" velocity log was developed in 1960 by the Birdwell Division of the Seismograph Service Corporation [37]. This system utilizes transmitting and receiving transducers placed a known adjustable distance from each other on an acoustically-isolating structural member [40]. The transmitter, located above the receivers, generates pulses of 22 microseconds in width at a rate of 20 per second. The waves are coupled between transducers and the bulk medium by borehole fluid. The receiving transducer detects any pressure waves reaching it in the borehole and converts these to electrical signals which are transmitted via cable, along with a synchronized pulse, to the surface recording equipment. The total wave train, including pressure, shear, and boundary waves, can be displayed in an intensity-modulated (or variable-density) format by a specially designed camera with a 210 mm fibre optic face. The 3-D system includes the combined down-hole package and the camera. The wave train presentation, in addition to time and in-hole distance markers, is recorded on film which moves past the face of the fibre optic tube in synchronization with the depth measuring device. The length of sweep is adjustable to display selected portions of the received wave trains ranging from 250 microseconds to 25 milliseconds.

Computer programs are applied to the raw data to compute corrected compressional and shear wave velocities; the Shear, Bulk, and Young's moduli; and Poisson's ratio. These elastic moduli are computed from theoretical relations developed for homogeneous, isotropic, and elastic materials and are in good agreement with other sources of information. The 3-D Velocity log has also been used in hole-to-hole logging operations. A range of about 200 ft. (61 m) is possible in this type operation in competent rock media [37].

The 3-D Velocity log has been used in single borehole investigations to determine porosity, evaluate cement bonds, locate gas zones, locate fracture zones, and determine elastic properties of rock. In particular, the amplitude of compressional and shear waves was found to be affected by fractures [40]. Shear waves were greatly reduced in amplitude by thin fracture planes, or beds, oriented traverse to the borehole axis, while compressional waves were only slightly attenuated. Fracture zones oriented obliquely were found to cause a reduction in both, and in highly fractured areas both were greatly attenuated. The effects of fractures, particularly thin fracture zones, have also been studied in laboratory efforts [41]. The orientation of the fracture planes was shown to have a selective effect in the relative attenuation of shear and compressional wave amplitudes. Other factors can also affect shear and compressional waves in acoustic logging operations. In general, these include tool centralization, mud properties, hole size, impedance match between hole mud and rock medium, borehole rugosity, attenuation of sound, geometrical spreading of the waves, velocity gradients, and boundaries at beds of different materials [41].

Some factors are more prominent in one system than another. For example, tool orientation and centering appear to be less of a problem in the BHC Sonic logging device than in others. There is, however, considerable commonality between the transmitted signal characteristics and the applications of the BHC Sonic and the 3-D Velocity logging systems. The major difference in the systems appears to be in the in-hole array and in data handling. Neither system is considered a direct candidate for the subject borehole system because of their limited range. However, both clearly demonstrate not only the feasibility but the practicality of in-hole acoustic logging systems and have fostered developments that could be directly applicable to the subject system. Some considerations pertinent to the subject acoustic system, called an acoustic pulse radar here, are discussed shortly. First, another borehole acoustic system, although not directly applicable here, is briefly mentioned because of some of its unique system features.

4.3.2.3 Borehole Televiewer

The Borehole Televiewer, developed by Mobile Research and Development Corporation around 1969, is an acoustic device which provides pictures of the borehole wall [42]. The device is also known as a seisviewer system.

The heart of the tool is a small piezoelectric transducer and a small flux-gate magnetometer. The transducer and magnetometer are rotated around the borehole axis by an in-hole motor at approximately three revolutions per second. The transducer emits a narrow beam of pulsed acoustic energy at a rate of 2000 per second. The acoustic signal travels through the borehole mud directly to the borehole wall and the reflected signal is detected at a receiving transducer. The amount of energy reflected by the borehole wall is a function of the physical properties of the wall surface. In general, any irregularities of the surface reduce the amplitude of the reflected signal and thus the intensity of the received signal. The signal is sent via cable to surface recording equipment. The magnetometer senses the earth's magnetic field and produces a pulse at the instant the transducer is pointed toward magnetic North. This signal is sent to the surface via the electrical cable. Operation of the in-hole system is also controlled from the surface by electrical signals transmitted through the cable.

The Borehole Televiewer is not a candidate for the present borehole application due to its range limitation. However, it illustrates the practicability of in-hole system positioning and control via external signals.

4.3.2.4 Dry Borehole Velocimeter

One example of a potential candidate for the acoustic probe is in the dry-hole velocimeter system developed by Southwest Research Institute. This employs piezoelectric discs for both transmitting and receiving. It has been used to generate and record compressional and shear waves in the 1-10 kHz band with ample strength to make acoustic pulse measurements in hard rock at useful ranges.

4.3.2.5 Simplec Borehole Probe

Another candidate for the acoustic probe has been developed by Simplec, Inc. This is a borehole probe that is currently in operation by the Tennessee Valley Authority. This uses magnetostrictive transmitting transducers and it has been reported that this system is able to resolve joints and gouge zones as little as 1/16" (1.6 mm) thick to distances in excess of 25 feet (7.6 m). Simplec manufactures probes using both magnetostrictive and ceramic transducers and they chose the magnetostrictive transducer specifically for this particular probe in the hard rock environment.

4.3.2.6 Sparker Acoustic Systems

Another possible candidate for this system is the sparker. Although the spark discharge approach has been used for years and was the initial form of transducer used in borehole logging, it has only recently been assembled in a form amenable for operation in a dry hole. The sparker basically is a discharge of a high-voltage electrical spark in a fluid (see Appendix E).

At the present time, there are no commercially available dry hole sparkers, although several manufacturers including Simplec, Inc. are investigating such a source. Moreover, there is some question about the safety of using high voltages in the borehole system. For these reasons, we do not recommend the use of the sparker for this system. However, if these problems are overcome, it should be seriously considered.

4.3.2.7 Exploding Wire Acoustic Systems

Similar in operation to the sparker is the exploding wire system. Instead of discharging a spark through an ionized gap, the exploding wire system physically uses a wire which is ionized and literally explodes when a high current is passed through it. One unit that is produced by Sonics International is packages for operation in a five-inch (13 cm) borehole. This system puts out a peak power in excess of 25 megawatts. It is not designed as an acoustic source for a system such as this. Its purpose is to physically blast scale and wax accumulations from the walls of pipes in producing oil wells. It is not believed that the exploding wire system would be a desirable candidate for this system. However, it is indicative of the amounts of power which are available using the general concept of the sparker.

4.3.2.8 Vibrator Systems

Another candidate to be considered is the electrodynamic vibrator. These units are available in a variety of sizes, shapes, and frequency ranges. They have the advantage that they can be made to be a repeatable, swept-frequency source. Physically, a unit that is three inches (7.6 cm) in diameter and can very easily be packaged to go into a borehole will provide a thrust in the order of ten pounds over a frequency range of from one hertz to ten kilohertz. It is primarily a continuous power rather than a pulsed power device. Thus, the signals must be processed before any display is possible. The pulse system or pulsed CW is considered to be a prime candidate. However, if for any reason the system concept changed so that a CW or a swept CW such as chirp type of system were employed, the electrodynamic vibrator would warrant serious consideration as an highly desirable, rugged, repeatable source of acoustical energy.

4.3.2.9 Acoustical Holography

Acoustical holography has the potential of penetrating into and reconstructing images of the structural features inside otherwise opaque media. Very briefly, the first step in producing the images is to record a "hologram". The hologram is formed by recording the interference patterns resulting from the interference between the coherent acoustic signal source and the signal reflected from the object of interest. There are several methods of recording the hologram. The hologram can be analyzed later to reconstruct images of the viewed objects. However, the presence of multipath propagation in the medium can cause serious errors. Multipaths are simply signals arriving at the receiver via different paths. There are several potential sources of multipath for acoustic propagation in subsurface media. For example, in a homogeneous rock with a single fracture plane, there may be a pulse reflected from the fracture plane which travels at P-wave velocity and a second pulse traveling at S-wave velocity. There may also be interface waves arriving at the receive point. The travel times of each may be different, which can result in an interference pattern (hologram) that, when used in reconstruction, indicates a series of fracture planes, one behind the other. Winter [43] has discussed problems of multipaths in acoustic propagation and suggests that they pose a serious obstacle to acoustic holography and imaging systems in general. Such problems may be circumvented as developments progress, but acoustical holography does not appear to be sufficiently well developed to be considered for the present program.

4.3.2.10 Acoustic Pulse Echo System

The BHC and the velocity logging systems discussed above could be referred to as acoustic pulse echo systems. They measure the transit time of pulsed acoustic signals which, with knowledge of the wave velocity in the medium, could be converted to range. However, they are specifically designed to investigate properties of the materials in the immediate vicinity of the borehole. Although the detection and measurement of range to distant targets is not their original purpose, the SwRI system could serve as the foundation for constructing a pulsed acoustic echo system to probe to the required ranges of 100 feet (30.5 m) or so. Presumably, the Simplec, BHC and 3-D systems could do so also, with suitable modification. A preliminary consideration to building such a radar, whether a new or modified design is pursued, is whether the desired range can be achieved without undue sacrifice of other performance requirements. In this regard, the most serious technical compromise among performance requirements is between the desired range and target resolution. It is experimentally established that the attenuation of acoustic waves in rock is approximately proportional to frequency [44], while the minimum target size that can be detected is inversely proportional to frequency.

4.3.3 SYSTEM CONSIDERATIONS

At this point in the preliminary development cycle, the dry hole pulse system is the preferred candidate for the acoustic subsystem. All indications are that the concept of dry hole pulse transmission is truly feasible. However, it is now necessary to consider a number of factors from the standpoint of total system tradeoffs involving available component suppliers and the functions which these components must perform. Most of these have already been mentioned. The signal type and the bandpass at peak power that the unit must provide must be balanced to realistic requirements for the tool. The pulse repetition frequency and the duty cycle which the source can handle dictate the amount of heat which must be transferred into the borehole. This can limit the traverse rate that can be obtained with this system. The physical size of the acoustic probe must be compatible with the borehole size. The lower frequencies required to achieve penetration in certain materials dictate the physical size of the magnetostrictive stack. In order to operate efficiently, their physical dimensions must be an appreciable portion of the lowest wavelength which they are expected to transmit. Thus, the stack must be as large as possible while still keeping the resonant frequency above the highest transmitted frequency. It will be necessary to evaluate the degree of compatibility which the existing acoustic components have when integrated into the whole system with the other types of probes and other system requirements. The physical restraints of the long borehole will reflect into system considerations from the standpoint of certain of the transducers. For example, the high-voltage transients required for an impulsive source cannot tolerate excessively long cables. This would imply that it would be necessary to package, in the limited downhole space, a high-voltage, high-energy discharge system which can be fed from a lower voltage source. All of these are factors which must be considered in the design. It is not sufficient to attempt to design the acoustic probe in a vacuum without considering the complete interplay between it and other probes involved.

There are discrepancies in the availability of the components necessary to fabricate a probe such as this. The majority of components are, however, available off-the-shelf. Some portions, principally the transducer contacting parts, will require additional development to meet the peculiar requirements of this program. Other factors which must be considered include reliability, safety, maintainability, potential traverse rates, and suitability of the signal to advanced signal processing techniques.

A preferred candidate certainly is a magnetostrictive pulse system. It is safe, convenient, and highly reliable. There is ample field experience in collateral areas from which to draw concerning its overall operational suitability. Conversely, it may be limited in range when compared to a sparker. The sparker has many advantages, the chief of which is high power. It has been well proven in high-frequency acoustic surveys under the ocean. However, it does not currently exist in the dry borehole configuration of an oil-filled elastomeric bag. Should such a device become available before the prototype is built, it should definitely be considered for this application.

Of primary concern at present is whether the desired range is feasible or not in realistic rock environments and within the bounds of reasonable transmitted power and available receiver sensitivity and with reasonable target size resolution. The wavelengths and power requirements for an acoustic system to detect a target of 1m^2 area in "good" (limestone" and "bad" (shale) environments are summarized in Tables 4 and 5 below (see Appendix D). Most of the time the operating environment of the borehole acoustic system will lie between these two extremes.

Table 4.

Wavelength and required transmitted power for a radar range of 100 ft. (30.5 m) in limestone.

f(Hz)	λ(ft)	λ(m)	P_t (milliwatts)
100	61	200	0.05
1,000	6.1	20	0.06
5,000	1.22	4	0.16
10,000	0.61	2	0.52
15,000	0.41	1.3	1.69
20,000	0.31	1.0	5.50
25,000	0.24	0.8	17.89
30,000	0.20	0.7	58.2

Limestone is one of the least attenuating rock types. Pierre shale is one of the more highly attenuating. Similar calculations for Pierre shale are shown in Table 5.

Table 5.

Wavelength and required transmitted power for a radar range of 100 ft. (30.5 m) in Pierre shale.

f(Hz)	λ(ft)	λ(m)	P_t(watts)
100	72.16	22	3.4×10^{-5}
1,000	7.22	2.2	4.7×10^{-3}
5,000	1.41	0.44	1.6×10^{7}
10,000	0.72	0.22	1.8×10^{24}
15,000	0.48	0.15	--
20,000	0.36	0.11	--
25,000	0.29	0.09	--
30,000	0.24	0.07	--

Assuming a lower limit on the size of a point target to be detected of about 3.28 feet (1 m), Tables 4 and 5 show that the lower limit of frequency is about 5 kHz for either limestone or Pierre shale. For linestone, the required transmitted power to achieve a radar range of 100 feet (30.5 m) is well within realizable values, even at 30 kHz. For Pierre shale, however, the power requirements become excessive at around 5 kHz. Assuming the practical limit on peak power is on the order of kilowatts, acoustic frequencies beyond some 1 to 5 kHz will not permit target detection at ranges of 100 feet (30.5 m) in Pierre shale. In limestone, however, the range may be larger than 100 ft (30.5 m) even at frequencies beyond 30 kHz. Hence, in some rock environments, the desired range of 100 ft. (30.5 m) appears quite feasible with acoustic radar, while in others it does not. The range as a function of frequency for various rock environments is treated further in Appendix C. It is also noted that acoustic radar range resolution considerations in terms of pulse width and range are analogous to those discussed for the monocyclic electromagnetic pulse radar in Section 4.2.

Acoustic pulse echo is a feasible candidate for the subject borehole sensing system. It is premature to judge whether it will be more or less beneficial than an electromagnetic pulse radar. However, it is clear that acoustic waves, whose characteristics depend on the elastic properties of the rock, and electromagnetic waves, whose characteristics depend on the electrical properties, have the potential of responding quite differently in the same environment.

4.4 CRITICAL EXPERIMENTAL DATA

4.4.1 INTRODUCTION

The design of this pre-excavation sensing system was handicapped from the start by a shortage of the kind of experimental data that is needed to validate the assumptions on which design decisions were to be based. Some of the kinds of information that were originally lacking include:

- Experimental estimates of the degree to which geologic features that are important to tunneling are discernable at long range by acoustic and electromagnetic probes.
- Experimental guidelines for the design and use of antennas and arrays in boreholes
- Experimental evidence on the degree to which the electrical response of important geolic features can be made to supplement their acoustical response in order to enhance detection.

In order to obtain some of the required information, it was found necessary to undertake the three experimental programs summarized below. (See Appendices K, L, and M for details of these programs.)

4.4.2 EM PROPAGATION AND PROFILING TESTS IN HARD ROCK

One of the most important experiments showed that E-M short pulse radar can indeed provide useful profiles through hard rock. The use of ground-probing radar to detect geolic hazards in advance of tunneling and heavy excavation had been proposed many times, but had not yet been adequately tested for practicality. There were conflicting reports on its probable usefulness, so these tests were conducted under the sponsorship of the National Science Foundation.

A commercially available electromagnetic radar was used, plus advanced signal processing techniques to provide geologic information in support of subsurface excavation technology. A crown drift of one of the future stations of the Washington, D.C. Metro system provided the test location.

4.4.2.1 Results of Field Tests

The tests conducted under this research have shown that even minor hard-rock joints are clearly detectable and traceable to ranges of six to eight feet (1.8 to 2.4 m). These test and the subsequent computer processing of the field data have demonstrated that:

- Major joint intersections can be traced to ranges of 40 to 50 feet (12-15 m) in medium-to-hard rock (schist).
- Reflections from the top of the main tunnel are clearly detectable from the crown drift more than 25 feet (8 m) away.
- Successful transillumination tests with the transmitter in the main tunnel and the receiver antenna in the pilot tunnel 25 feet (8 m) away proved the capability of EM radar to penetrate hard rock with median transmission characteristics to significant depths.

4.3.3 RELATIONS BETWEEN ACOUSTIC, ELECTRICAL, AND STRENGTH PARAMETERS OF ROCK

From the very beginning of this project, the need for more information about the physical properties of low-porosity rock was quite evident.

After the decision to use acoustics, electromagnetics, and electrical sensors was made, it was apparent that a need to have relevant correlations among the electrical, acoustic, electromagnetic, and strength parameters had to be satisfied.

A contract was negotiated with Colorado School of Mines to obtain some of this information. The results are summarized below and are given in detail in Appendix K.

Acoustic, mechanical and electrical properties have been measured on suites of low-porosity rocks. Three rock types were represented in these suites; gneiss and schist, granite, and metarhyolite. All are similar in chemical makeup, but differ materially in texture. The three rock types exhibited a wide range in unconfined compressive strengths, ranging from 5000 to 75000 pounds per square inch (34.47 to 517.11 MPa). Many of the measured properties, such as density, acoustic wavespeeds, and dielectric constant, show a pronounced correlation with strength. However, in each case, a significant number of data contradict these correlations, so that the correlations would have to be used cautiously in inferring rock conditions from geophysical measurements.

Measurements of electrical properties indicate that conductivity and dielectric constant in water-bearing samples are nearly independent of frequency out to frequencies of approximately 1 gigahertz. Attenuation rates for electromagnetic waves at frequencies ranging from 100 megahertz to 1 gigahertz should be 0.6 to 6 db per meter, for rock resistivities ranging from 100 to 1000 ohm-meters. These estimates bode well for the use of radar imaging in the more resistant parts of rock masses consisting of gneiss, granite, or rhyolite.

4.4.4 ANTENNA TESTS

Early in the program, it became important to investigate the capability of radar antennas to resolve the location of anomalies in planes normal to the borehole.

To this end, Dr. John C. Cook, ENSCO consultant, and ground-probing radar pioneer, performed a study on various antenna configurations. This work is described in Appendix L and is summarized below.

The purpose of the experiments was to estimate the directional sensitivity that could be expected from the null patterns of a dipole antenna in a borehole.

Dr. Cook explored this question by employing a transverse-dipole type of antenna, which may have a radiation pattern containing nulls (directions of zero sensitivity) in the plane transverse to the borehole. If such an antenna were rotated so that a null zone embraced the anomaly, its reflected signal should vanish. This would provide the needed localization. The work was performed to test the general feasibility of such a technique.

For speed, convenience and least cost, these experiments have all been performed in air rather than in rock; it is likely that the results obtained in air are applicable to any other isotropic medium of propagation, providing the rules of electromagnetic modeling are kept in mind. In general, the antenna dimensions, or operating frequency, must be reduced by the factor $\sqrt{n}$ when an antenna operating in a medium having magnetic and dielectric constants ($\mu\varepsilon$) is immersed instead in a medium of constants $\mu'\varepsilon'=n(\mu\varepsilon)$.

All of the tests have been made with magnetic dipoles (loops) as receiving antennas, because these are readily made with the plane of polarization in line with the borehole. This in turn is compatible with the electric-dipole type of borehole antenna already developed for transmitting.

The transverse magnetic-dipole antenna must simultaneously fulfill three requirements:

1. Directivity in the plan transverse to the borehole, with at least one null.

2. Reasonable efficiency. This in turn means as large an area as is permitted by the wavelength, and a fair impedance match to the 50-ohm transmission line and receiving equipment.
3. Broad-bandedness of one or more octaves, to receive short rf ("monocycle:) pulses without excessive distortion.

The objectives have all been achieved, as detailed in the following:

1. A magnetic dipole antenna has been found which is capable of being used in a four-inch (10 cm) diameter borehole, which receives 100 to 200 MHz "monocycle" radar pulses without serious distortion at acceptable sensitivity, and has broadside "null" zones of at least 20 dB lower sensitivity than the edgewise maximum zones. Other borehole loop designs also shown promising directivity and higher sensitivity.
2. The width of the null zones of this same antenna is of the order of 10 degrees. The direction of a "point" source or specular reflector could be determined to within 5 degrees, or better.
3. The 180° ambiguity expected seldom occurs in practice. One radiation lobe is generally stronger than the other. Some antennas have only one maximum and one minimum.

This work has been confined to the exploration of feasibilities. Directional borehole antennas are almost certainly possible. Practical engineering designs for such antennas will require additional development work.

4.4.5 CONCLUSIONS

These experiments, even though quite limited in scope, provided an important fraction of the experimental data needed to complete the design of the electromagnetic portion of the borehole sensing system. They showed that E-M short-pulse radar profiling in rock will work, and provided some guidelines for selection of signal parameters and processing requirements.

Much experimental work remains to be done before the system design should be frozen in its final form. More information is needed on the performance of the acoustic subsystem and on how best to use the combined acoustical and electrical responses of important geologic features to assure their detection and location. More experimental work needs to be done to identify and solve all the operational problems that will be encountered in the borehole.

Early operation of the prototype system itself is the best and most timely way to acquire the required experimental information. The early acquisition of field experience with the prototype was a major objective in the decision to base the prototype system design on a modular concept.

4.5 SUMMARY

This effort narrowed down the wide variety of methods of geophysical exploration to electrical, magnetic, electromagnetic and acoustic (seismic and sonic) methods, as shown in Figure 13, and of these, identified the three methods most applicable to sensing discontinuities and anomalies in rock from within a horizontal borehole. These are: acoustic pulse radar, electromagnetic pulsed radar, and resistivity probes.

Some of the rejected methods were eliminated because they are relatively unsuitable for obtaining structural details near the borehole. These include all methods which cannot have their power source and receiving transducers within the borehole. In particular, this excludes from further consideration methods such as airborne surveys, surface-to-surface, surface-to-borehole methods, and those that utilize power sources of opportunity such as the earth's natural electromagnetic field, earth tremors, and existing radio broadcast stations. Magnetic methods are also readily excluded because their major application is the detection of naturally occurring magnetic materials, and these have no correlation with rock characteristics of major importance in tunneling.

Several types of electrical and electromagnetic methods are used in well logging and were considered initially as potential candidates for the subject borehole application. They are broadly categorized in terms of contacting, induction, and electromagnetic methods.

The contacting methods reviewed for their capability to measure average resistivities (which are correlated with rock strength) include spaced multiple electrode, focused current, microspaced and polarization. The spaced multiple electrode method is deemed the more applicable of the contacting methods. The

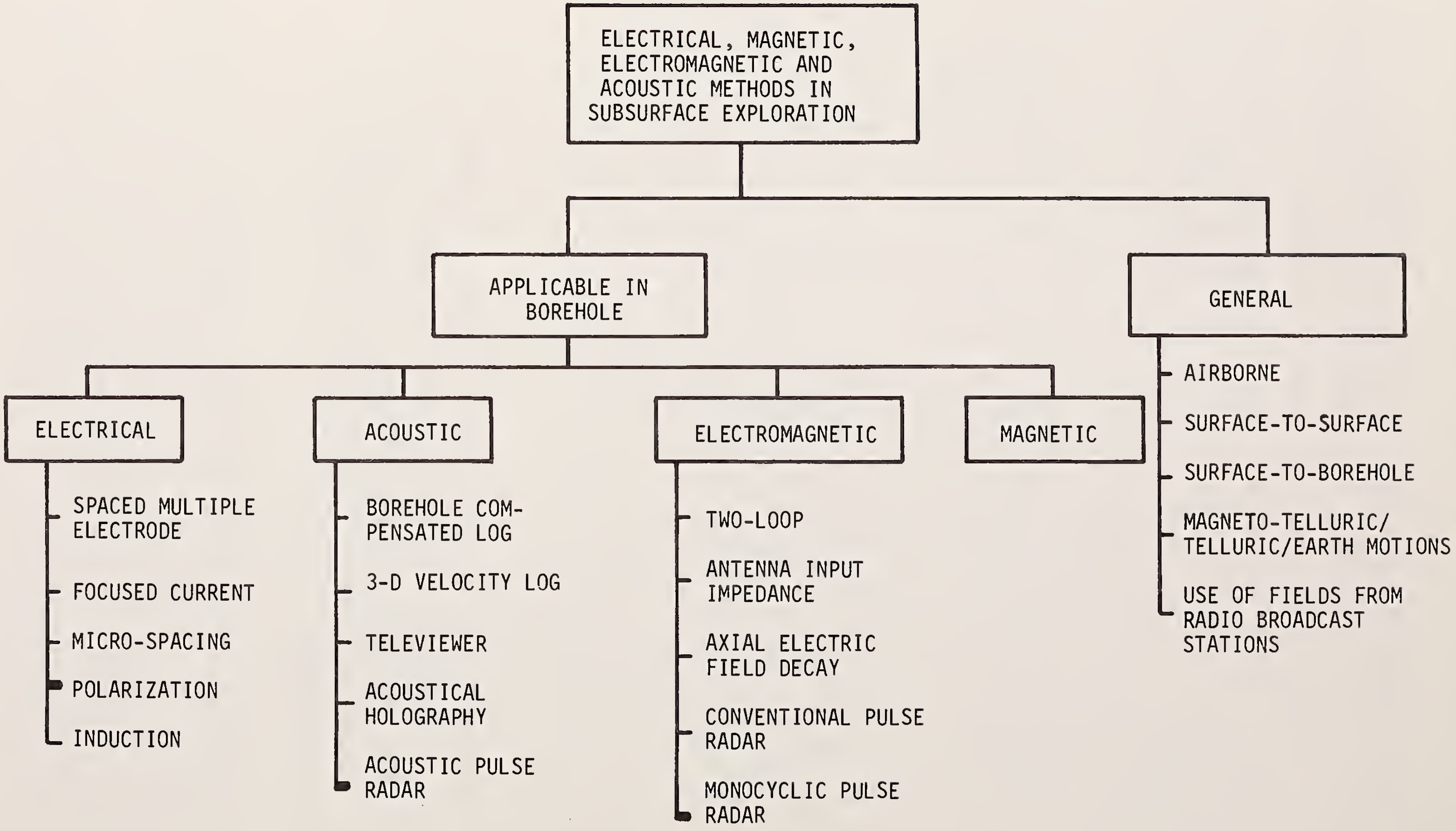


Figure 13. Summary of electrical, magnetic, electromagnetic and acoustic methods reviewed. Candidates selected for the borehole sensory system are identified by darker lead-lines and capitalization.

focused current and micro-spaced methods are deemed unsatisfactory because of their complexities and limited range, respectively. Polarization methods are considered as candidates because they give additional data at virtually no additional cost when used in conjunction with the spaced multiple electrode method.

The induction method is not considered a suitable candidate because it requires a prior knowledge of the conductivity to within about an order of magnitude to properly configure the system and interpret the data. Also, it yields resistivity data which is more simply obtained with the spaced multiple electrode method.

Electromagnetic methods reviewed for their applicability in determining average parameters are two-loop, antenna input impedance, and axial electric field decay. The two-loop method is not considered as a competing candidate because of the relative difficulty in data interpretation and limited history in geophysical interpretations as compared with the spaced electrode methods. The antenna input impedance and axial field decay methods are not considered as candidates because of potential inaccuracies due to drilling mud and rock fragments in the former and the need for prior knowledge of the dielectric constant of the rock in the latter.

A monocyclic, or video, pulse radar is considered the most suitable candidate electromagnetic radar method for detecting, locating, and identifying rock discontinuities near the borehole. Conventional radar methods have unsuitable pulse characteristics which do not permit detection of discontinuities very near the radar transmitting antenna. Other radar methods, such as those employing chirp techniques, have not been as fully developed for subsurface applications as the monocyclic radar.

Acoustic methods reviewed for their applicability are a borehole-compensated (BHC) sonic, three-dimensional (3-D) velocity, and televiewer logging systems, a dry-hole velocity logging system, three types of source for "acoustic radar", and acoustic holography. The most attractive candidates for incorporation into the prototype system are elements of the dry-hole acoustic systems of SWRI and of Simplec, Inc. (see Appendix E).

5. BASELINE SYSTEM CONFIGURATION

5.1 SELECTION OF BASELINE SYSTEM

Following the initial functional analysis, a "baseline" system was synthesized which would meet the functional and operational requirements of the system. The baseline system is not the same as the prototype system that evolved from it. The purpose of the baseline system description was to provide a standard for estimating the total impact on the system of changes proposed during the evolution of the prototype system.

The baseline system chosen is derived from an analysis of the probable technical evolution of the system, and of the most cost-effective method of achieving these goals. The technical studies, Section 4, indicate that the sensor system should include three sensing techniques: electromagnetic radar, acoustic radar, and electrical resistivity logging. A prime consideration in arriving at the baseline system was the evaluation of the best method of employing these techniques in an overall system configuration.

The baseline system described herein provides only a reference standard of one feasible way of accomplishing the program goals. It was based on a preliminary optimization and was expected to change as the system studies progressed.

In arriving at the baseline system configuration, two major alternatives were considered:

- Provide a single integrated system with all three sensors in a single package
- Provide a modular system consisting of a central system containing those functions common to the use of all three sensors and individual packages containing the individual sensors

The integrated approach has many advantages:

- Its operational costs would be lower, in that only a single run would have to be made into a hole.
- The chances of getting completed data would be better in that the hole would only have to be used once.
- Better data could be obtained. Data would be simultaneously available from all sensors. The Field Test Operator could better judge the quality of his data by comparing returns from unlike sensors.
- Data reduction would be simplified in that the taped data sent to the Data to Information Conversion Center (DICC) would already be correlated with respect to the location from within the hole.

There are several major disadvantages for the integrated system:

- The system will be more complex
- It will be large and cumbersome
- The length of the package would be such that the propulsion system would have to be in front of the package to pull the system into the hole. This presents the unresolved technical problem of transmitting propulsive power past the sensors.
- There is greater risk of jamming the package
- The development costs would be higher
- The development cycle would be prolonged by at least a year.

The advantages of the modular system are:

- Lower development cost, time, and risk
- Initial use of available downhole equipment such as the Birdwell 3-D velocity log, and standard resistivity logging devices
- Greater flexibility in modifying sensor packages

- Simpler surface and telemetry equipment
- Adaptability to other sensors not presently included in the prototype system
- Lighter, better propulsion system which pushes rather than pulls the sensor package.

The major disadvantages of the modular system would be:

- Higher operational costs
- Higher operational risk of hole re-entry problems
- More cumbersome data reduction procedures.

There are many fundamental questions concerning how best to develop, operate, and exploit a system such as this. These can only be resolved on the basis of experimental data derived from the use of the system in the field. It is believed that the initial developmental resources could be used more effectively in concentrating on the resolution of these fundamental questions than in integration of components into a more advanced system whose feasibility has not been field tested.

The modular unit can provide the answers to these questions at lower cost and a shorter development cycle and much less technical risk. Therefore, it has been selected to form the baseline system. The system described consists of an assembly of technically feasible subsystems. Each subsystem has been selected on the basis of considerations of alternative solutions; thus, they represent the best current thinking on the optimum configuration.

5.2 DESCRIPTION OF BASELINE SYSTEM

The baseline system will be discussed here as an entity without repeating the alternatives which were considered. These are covered in Appendix A.

The form of the discussion will, in general, follow the Functional Analysis of Section 3, starting at the nose of the Downhole Package.

5.2.1 DOWNHOLE PACKAGE (DHP) (FIGURE 14)

The Downhole Package will consist of three physically separate sections: the penetrator and guidance section, the modular sensor section, and the power and propulsion section.

- Penetration and Guidance. The penetration and guidance section will consist of a rotating steerable conical nose which will lead the package into the hole. It will be physically connected to the front of the sensor package. However, there will be no electrical or power interface. For control and status monitoring, it will be connected to the power and propulsion section by a two-way wireless telemetry link which bypasses the sensor section.

  The penetrator will operate as a reverse auger, whenever a blockage is sensed. It will turn on and rotate so as to shove the blockage forward. It will spread small debris, less than 1/2 inch (13 mm) in size around the wall of the borehole, so as to allow the Downhole Package to pass. Debris larger than 1/2 inch (13 mm) will be pushed ahead of the unit.

  Guidance will only be required where a hole has been redrilled and there is a fork. This can be determined from the driller's log. The conical nose must be steerable so that it can select the proper branch to take. Power for the entire section will be supplied by batteries. If jammed, this section will be designed to break loose so the rest of the package can be withdrawn and salvaged.

- Sensor Section. The sensor section will be a modular insert in the Downhole Package. Each sensor subsystem will be a self-contained entity. They all will be designed to meet standard physical and electrical interfaces with the power and propulsion section behind and physical interface only with the penetration and guidance section in front.

  Where power other than that available through the standard interface is required, it will be supplied by internal batteries. The standard interface will supply communication channels for control and status monitoring. Data will be converted to standard analog voltage levels for transmission to the surface.

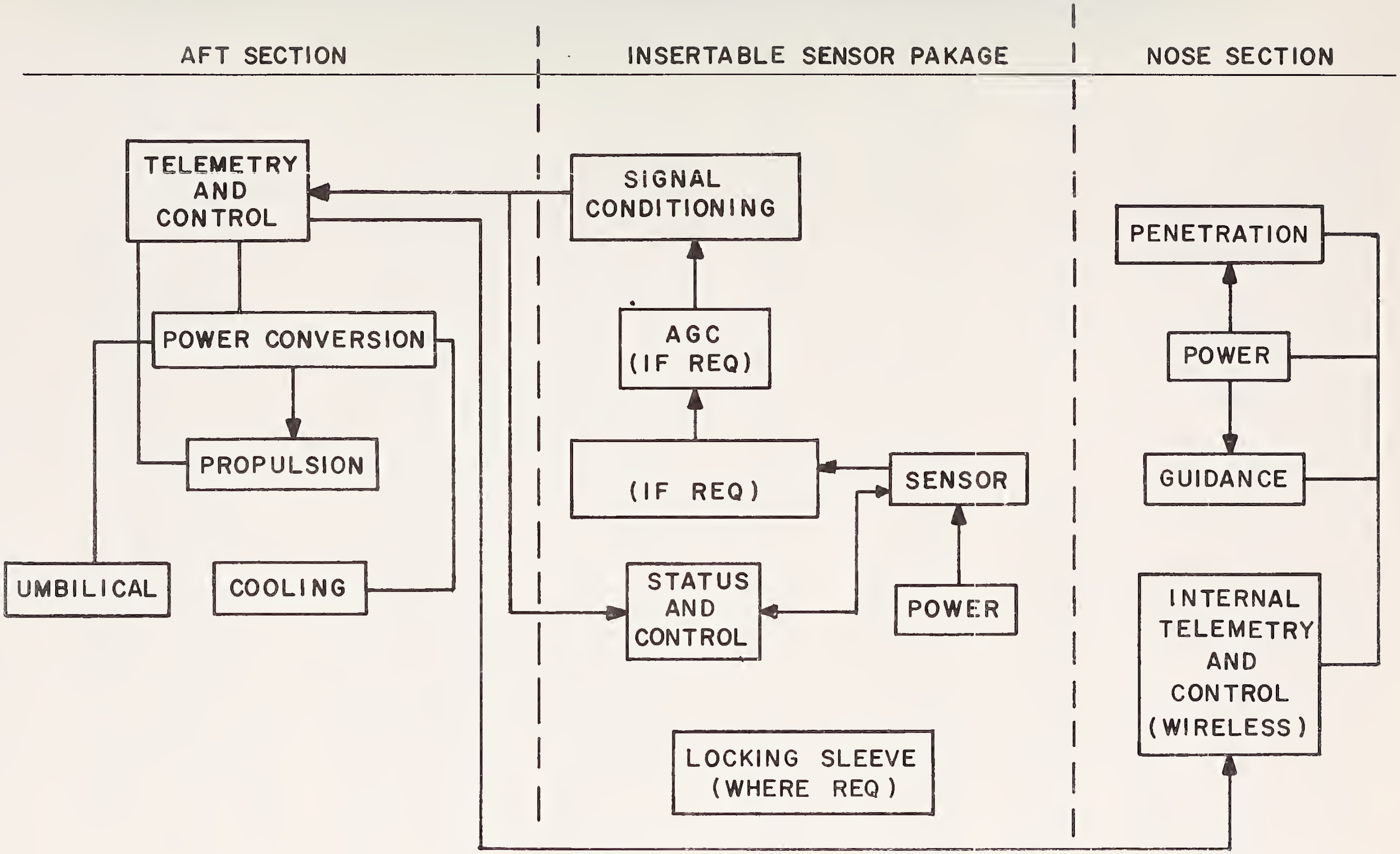


Figure 14. Down hole package.

The acoustic radar and the resistivity packages will have to make firm contact with the walls of the borehole. This will be accomplished by an elastic skin which must be inflated whenever a reading is taken. The outer skin diameter will be just smaller than the borehole diameter so that minimum fluid flow will be required for its inflation. Hydraulic power will be supplied through the interface and synchronized with the propulsion system.

- Power and Propulsion Section. The power and propulsion section will handle all functions aft of the modular sensor package. It will contain:

  A telemetry and control package which handles the communications, control signal conditioning, and line driving functions. Telemetry will be by analog frequency modulation; status control, and data function will be on separate FM channels.

  A propulsion system operated by hydraulic power and working on a linear thrust and locking cell principle. It will be adaptable to various hole diameters by special fluid-filled adaptor sleeves.

  A power conversion system which takes high-voltage, low-current 60 Hz power from the umbilical system and transforms it to usable power levels. It also contains an electrical to hydraulic power converter to provide hydraulic power to the propulsion system and the expansion cells of the sensor packages.

  A cooling system, which is designed to take the heat from the power conversion system and the propulsion system, and transfer it into the borehole wall. This may be accomplished by an inflatable skin of high thermal conductivity which is inflated in synchronism with the locking cells of the propulsion system.

5.2.2 UMBILICAL (U)

The Umbilical will be a custom logging cable. It will consist of a pair of high-voltage insulated wires for power transfer, a coaxial cable for transfer of data status and control signals, and a signal pair for transfer of control signals from the surface.

5.2.3 SURFACE SUPPORT SYSTEM (SSS) (FIGURE 15)

The Umbilical is connected to the Surface Support System via the cable drum. Inside the drum is a transformer which raises the voltage from normal line to high voltage for transfer down the cable.

Line voltages are transferred to the drum by high current slip rings, while signals leads enter and leave and drum by low noise slip rings. 60 Hz power comes from an auxiliary trailer-mounted motor-generator.

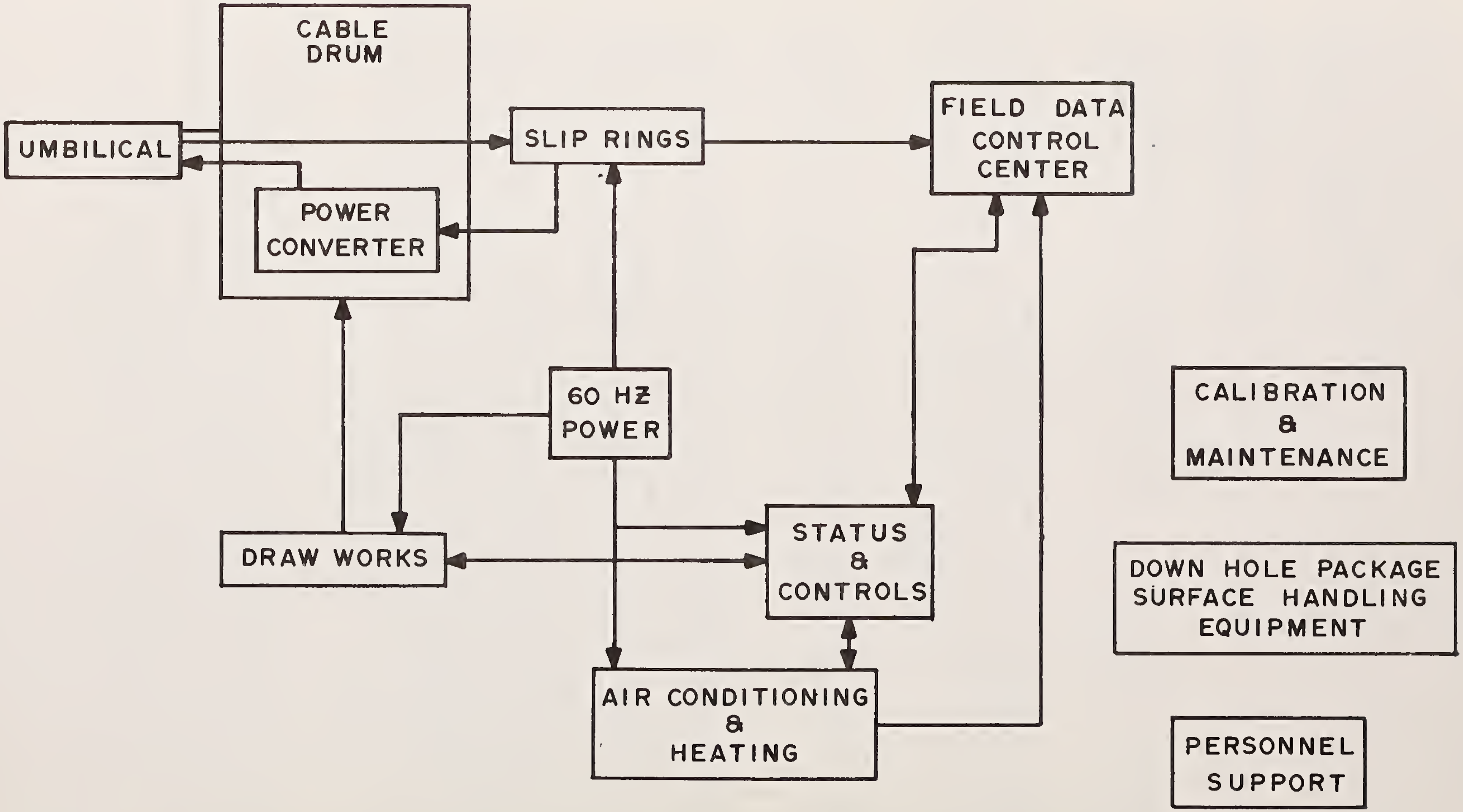
The draw works are remotely operated from the Field Data Control Center which is housed in a compartment behind the draw works. It is air conditioned and heated, both for crew comfort and for the protection of the equipment.

The balance of the surface support system is as described in paragraph 3.2.4.

5.2.4 FIELD DATA CONTROL CENTER (FDCC) (FIGURE 16)

The final terminus of the Umbilical system is in the FDCC. The signals are properly conditioned for transmitting downhole, and the upcoming signals are demodulated. The status signals are separated and go to the operator's console where they are displayed. The data signals pass through an analog-to-digital converter for recording on magnetic tape. They are also decoded again in a digital-to-analog converter. This insures that the displayed signals are the same as those which are recorded.

The display by which the operator evaluates the quality of the recorded data will be an xy recorder. It will operate in two modes. In the rectangular mode, the time-of-flight of signal returns will be plotted against displacement along the hole, and in the polar mode, the time-of-flight will be plotted against azimuth with respect to the vertical.



SURFACE SUPPORT SYSTEM

Figure 15. Surface support system.

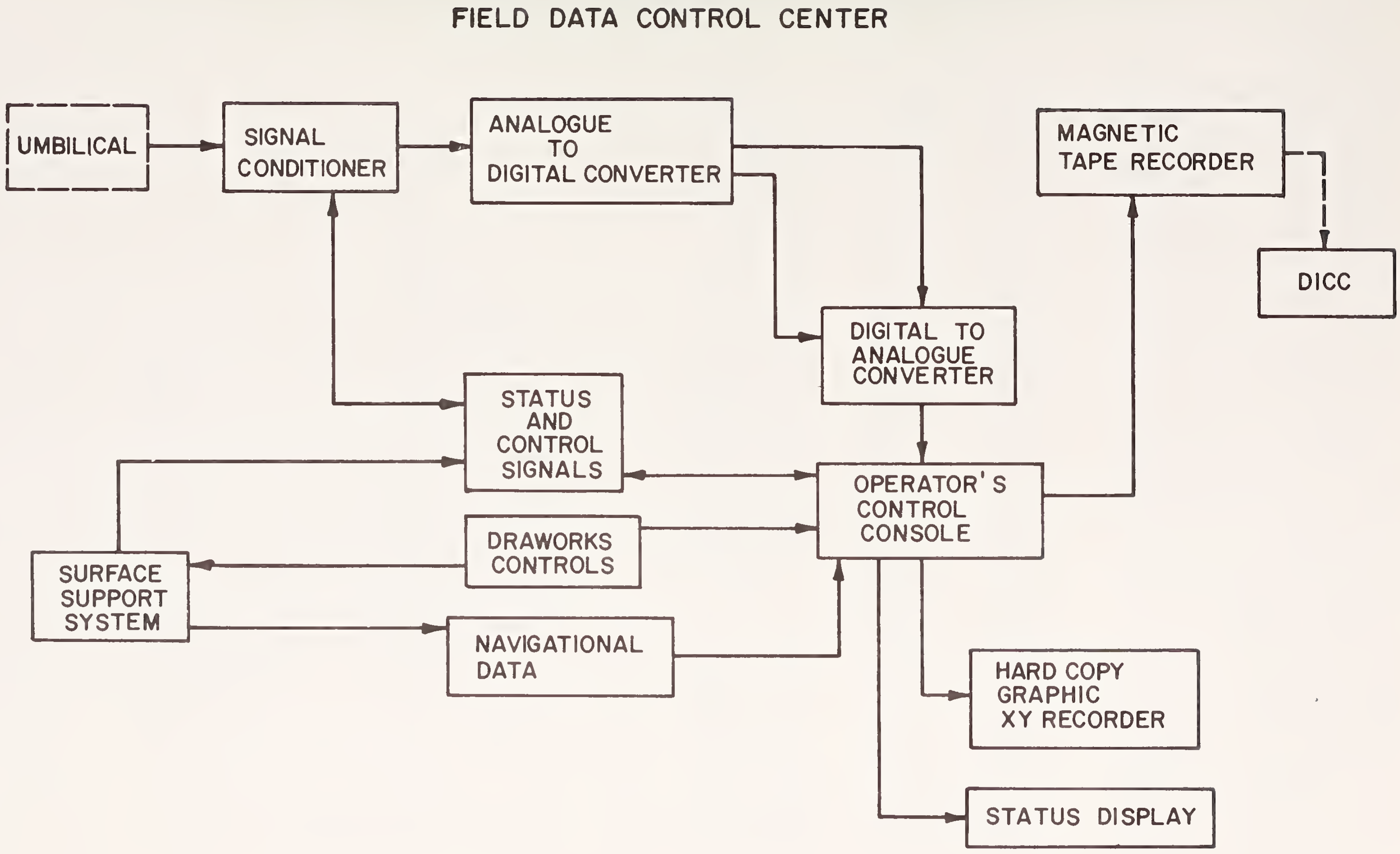


Figure 16. Field Data Control Center.

The data will normally be displayed in polar azimuthal format. However, the operator will have the capability of rerunning any block of recorded data in an xy format, to display a linear traverse at any selected azimuthal angle.

The Field Test Operator will be able to evaluate and control the performance of the system from his console. His displays will include:

- Go/no-go lights giving the status of all critical subsystems both in the Downhole Package and on the surface.
- Analog or numeric display of navigational information including depth of package in the hole, the azimuthal orientation of the package, and
- Analog or numeric display of critical operating parameters such as fuel reserves, tape footage, cable tension, time and temperature. This may include data on controllable downhole parameters such as equipment operating temperature and force buildups on the nose of the penetrator.

He will have controls for:

- Transit speed within the hole
- The amount of data taken at any point
- Critical sensor parameters such as pulse width, receiver gains, transmitted power, and the automatic gain control function
- Tape speed
- Operating modes
- Display modes
- Start-up and shut-down procedures.

There will be a voice channel on the tape to inform the DICC of key features and operational aspects which may be of value in reducing and interpreting his data. There will also be a keyboard so that precoded instructions to the computer in the DICC can be entered onto the tape. Normal operating modes and instrument settings needed in reduction of the data will automatically be entered on the tape. Special information, such as a rerun of a certain section of the hole, or a special test, would be keyed in manually.

The general design philosophy of the control console will be that sensor packages may be changed and modified. However, this should not reflect major design impact on the rest of the system. The control console and the operator must have the flexibility to accept these changes without major redesign.

6. COST AND COST-EFFECTIVENESS STUDIES

6.1 INTRODUCTION

This section summarizes a series of cost and cost-effectiveness studies made during the course of this contract. The section starts with a study that justifies the use of boreholes in place of pilot tunnels as a means for obtaining the geologic information necessary to insure safe and efficient construction of the tunnel. The studies proceed to determine the optimum size of the borehole and then to perform risk analysis for the system development. The economic analysis of the integral system provides a basis for final specification of the system. The final system studies are contained in the last parts of the section.

The cost study for the modular system shows an extremely cost-effective way to proceed with the system development. This system allows us to design a system with state-of-the-art components which can be constructed and put into the field in a minimum amount of time. Then, as operational experience is gained, it will be possible to make improvements to the individual subsystems as the user demands them. Improvements will be on the basis of the users' economic demand. Thus, the economic balance dictates that the increased costs will accrue only if, on a cost-effectiveness basis, they permit a greater savings in some other aspect of tunneling. Since this is the ultimate goal of the system, we believe the modular approach is the best way to meet the goal.

6.2 COMPARATIVE COSTS OF BOREHOLES AND PILOT TUNNELS

A study of the estimated cost of pilot tunnels is provided in Appendix P. Since relatively few pilot tunnels had been excavated in the United States at the time the study was made, reported data were used from 17 lined tunnels in sizes comparable to pilot tunnels contracted in the period 1956 through 1973. The costs of excavation and basic support only were taken from the data, and these costs were updated to a common 1974 base. The adjusted costs were then converted to costs per cubic yard and applied to an 8 feet x 10 feet (2.4 m x 3 m) tunnel section in order to estimate the costs of standard pilot tunnels shown in Table 6.

Table 6. Projected costs for pilot tunnels.

	Excavation Costs			
Category of Ground Conditions	\$/cubic yard Base Year: 1974		8' x 10' Tunnel Base Year: 1974	
	$\$/\text{yd}^3$	$\$/\text{m}^3$	\$/ft	\$/m
Difficult	\$296 ± 10%	\$387 ± 10%	\$877 avg.	\$2877 avg.
Normal	\$120 ± 15%	\$157 ± 15%	\$356 avg.	\$1168 avg.
Easy	\$ 76 ± 20%	\$ 99 ± 20%	\$225 avg.	\$ 738 avg.

Information on the costs of pilot tunnels in the Washington, D. C. area that supplements the study in Appendix P confirms the validity of using the Construction Cost Index of the Engineering News Record to update cost estimates for pilot tunnels. The index average for 1975 was 9.5% higher than the 1974 average, and the average for the first three months of 1976 was 9.2% higher than for the same three months of 1975. Accordingly, we can estimate that average 1976 costs will be 20% higher than the costs indicated in Table 6.

Since the costs shown in Table 6 were derived from the tunnels listed in Appendix P, they will apply to tunnels of the average length of those listed or about 2,000 ft. (609.6m) long. Costs per unit length tend to rise with increase in lengths of tunnels because of haulage, travel, ventilation, drainage, and many other construction factors that increase faster than the length of tunnel increases. Mobilization and overhead costs generally increase at lower rates.

Figure 17 is a comparative plot of pilot tunnel costs and projected borehole drilling costs. The tunnel costs in 1974 dollars were taken from the data for tunnels listed in Appendix P. Tunnel costs were reduced proportionately for the smaller 8 ft. x 10 ft. (2.4 m x 3.0 m) pilot tunnel section except in the case of the small tunnels at Littlefield, VT, and Straight Creek, CO, as the unit costs of unlined tunnels tend to remain constant up to 12-foot (3.7 m) diameter.

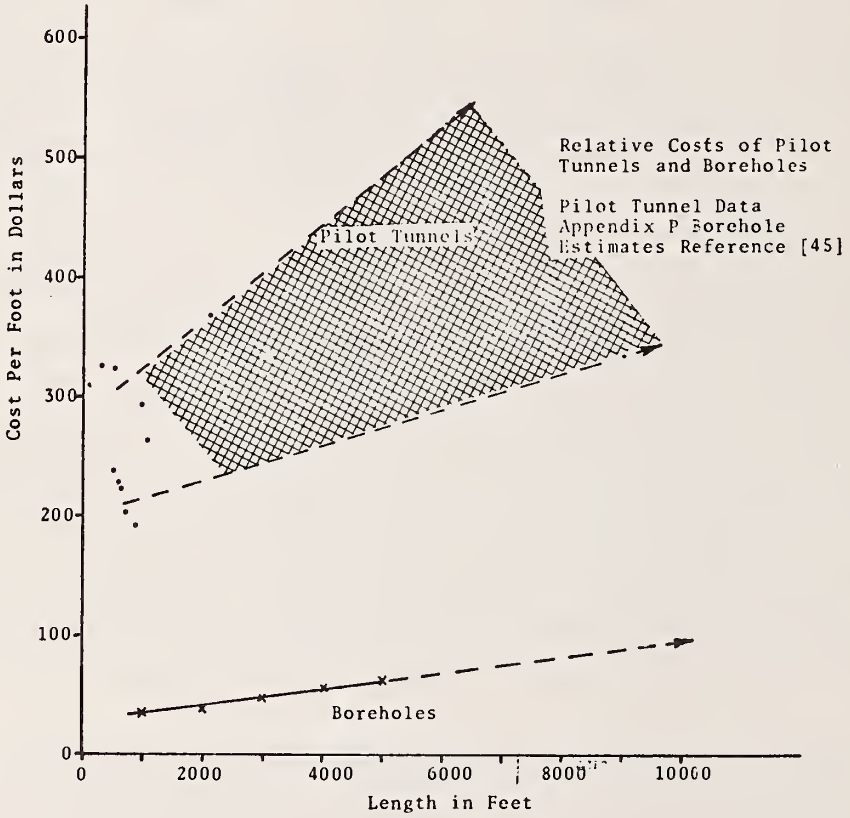


Figure 17. Relative costs of pilot tunnels and boreholes.

The costs of five of the tunnels listed in Appendix P were omitted, as they are not considered representative. The two tunnels in Alaska were omitted, as construction in Alaska usually costs more than twice as much as in the 48 contiguous states; the cost of the tunnel in Hawaii is an estimate; and the tunnels at Oche, SD, and at Hills Creek, OR, were excavated under very difficult conditions and at exceptionally high costs.

The estimates for borehole costs to 5,000 feet (1,524 m) were taken from Table A.18 of Reference [1] for diamond wireline core drilling. These costs are in 1974 dollars. The relation between rising construction costs and improvements in the drilling of boreholes that tend to reduce costs are not clear; therefore, estimates for future costs are difficult.

The trend lines shown in Figure 17 are considered to be only general indicators. They are not statistically accurate because of the few data points available and the widely-varying conditions that were met in tunneling. However, the average costs for pilot tunnels projected in Table 6 are strikingly higher than for boreholes. Projected costs are compared in Table 7. The ratios in this table were obtained by comparing data from Table 6 to estimates for borehole from Reference [1], using a $75 per foot ($248 per m) average of the estimated cost of wireline core drilling and rotary drilling for a 5,000 foot (1,524 m) borehole.

Table 7.

Cost ratio of pilot tunnels to boreholes.

Geologic Conditions	Cost Ratio
Difficult	11.7/1
Normal	4.9/1
Easy	3/1

It should be noted that the approximate limit of state-of-the-art horizontal drilling is 5,000 feet (1524 m). The developments necessary to extend holes to 10,000 feet (3048 m) and beyond are of the nature to also reduce the drilling cost per foot. Thus, the already significant cost advantage of boreholes over pilot tunnels can be expected to be even more striking in the projectable future.

Improvements in working conditions made to comply with health and safety regulations have the short term effect of reducing productivity and increasing costs. However, over long periods the adverse effects that improvements in working conditions have on costs seem to be balanced by improvements in equipment and methods and by reductions in the costs of injuries and lost time. Therefore, these safety regulations should have little effort on overall costs.

Until recently, wages and benefits were the dominant factors in the escalation of construction costs. In the future, rising energy costs can be expected to dominate.

6.3 SENSING COST-BENEFIT RATIOS AS A FUNCTION OF BOREHOLE SIZE

There are few technical factors in the sensing system itself which limit the size of the borehole. In general, the larger the borehole the better the data. There will be a point where the borehole becomes so large that it will be difficult to operate the sensing systems which must contact the wall (i.e., acoustic and electrical). This is one major problem with the sensors in large borehole diameters. Another limiting factor for going to large diameter holes is the cost of drilling.

There are two factors which govern the minimum size for a sensing package. The first is the efficiency of coupling energy into the rock. Extremely small diameters limit the size of the antennas which can be used. This decreases both efficiency and resolution in the resulting system. For reasonable results, the borehole should be on the order of one-quarter wavelength in diameter. Previous work has determined that the frequency range for electromagnetic radar will be about 100 MHz-200 MHz. With a relative dielectric constant of eight, this would imply wavelengths of the order of 42 in. (1.07 m) to 21 in. (53 cm) respectively. Thus, a six in. (15 cm) diameter would be the minimum diameter for a radar. The acoustic transducers will produce energy with the same wavelength and will require the same size hole. A six-inch (15 cm) borehole is a reasonable choice for another reason in that the packaging problems for a six-inch (15 cm) borehole will be at least four times (the ratio of volumes) easier than packaging for a three-inch (7.6 cm) borehole. Developing hydraulic systems and mechanical components for smaller than three-inch (7.6 cm) boreholes becomes more difficult and at least an order of magnitude more costly.

At present, horizontal holes can be drilled in NX [diameter of three inches (7.6 cm)] and less, to distances in the order of 1,000 feet (304.8 m). Drilling in hard rock will require either a diamond bit or a roller cone cutter of some type. Diamond drilling in the large sizes is uneconomical except for coring or drilling in hardest rock. As hole sizes get smaller, roller cones become less reliable because the available bearing area becomes marginal. Six and three-quarter inches seems to be the smallest size where a wide range of roller cone bits is available.

A more complete discussion of tradeoffs involved in hole size is included in Appendix Q, but for this prototype the optimum hole size seems to be about 6-3/4 inches (17 cm). This diameter is small enough so that drilling costs are low, yet large enough so that it will be possible to drill holes to distances of a few thousand feet. The hole is also large enough to use easily obtainable components in the packaging of the system components.

6.4 ECONOMIC ANALYSIS OF THE INTEGRAL SYSTEM

The purpose of this section is to examine the estimates of the development and operating costs of the proposed integral system. Preliminary cost estimates of the system and subsystems serve to identify relative costs and provide valuable guidelines for selection of the more cost-effective alternatives in the system design.

The system development costs presented encompass all identified costs in the development cycle of the system. The development cycle is conveniently separated into the following phases:

- Phase I - Feasibility Analysis and Design
- Phase II - Prototype Fabrication and Test
- Phase III - Field Test and Evaluation
- Phase IV - Fabrication and Acceptance Testing of an Operational Model.

The feasibility analysis and design phase is being done under the present contract by ENSCO, Inc. Hence, the associated costs are known to be about $250,000.

The majority of the components and subsystems of the proposed system will be newly developed items and items which require modifications or repackaging. Hence, in general, hardware does not exist for which the prototype development costs can be obtained directly. Therefore, a large amount of subjective judgment based on past experiences must be used. A more thorough discussion of estimating procedures is contained in Appendix O.

The estimate of costs for Phase II, Prototype Fabrication and Test, is shown below.

System	Cost
Downhole Package	$282,000
Umbilical	63,000
Surface Support System	53,500
Field Data Control Center	175,000
Data-to-Information Conversion Center	76,500
TOTAL	$650,000

Phase III, Field Test and Evaluation, will last about a year and will be a three-to-four man effort; therefore, the cost will be about $150,000. Phase IV, the Fabrication of an Operational Model, will be about $375,000. This includes redesign and rehabilitation of the prototype system, construction of a second downhole package, and redesign of data processing support system. The total system costs are shown below.

Phase I - Feasibility Study and Design	$250K
Phase II - Prototype Fabrication and Test	650K
Phase III - Field Test and Evaluation	150K
Phase IV - Fabrication of Operational Model	375K
TOTAL	$1,425K

These costs will be distributed over the number of years required in the developmental cycle. During this time, the associated costs will bear interest. In estimating the interest charges, it is assumed that the interest rate will be 10%, compounded annually. The estimated development schedule is shown in Figure 18 with the development phases, their duration and costs identified.

In estimating the amortization costs for this system, the following are assumed:

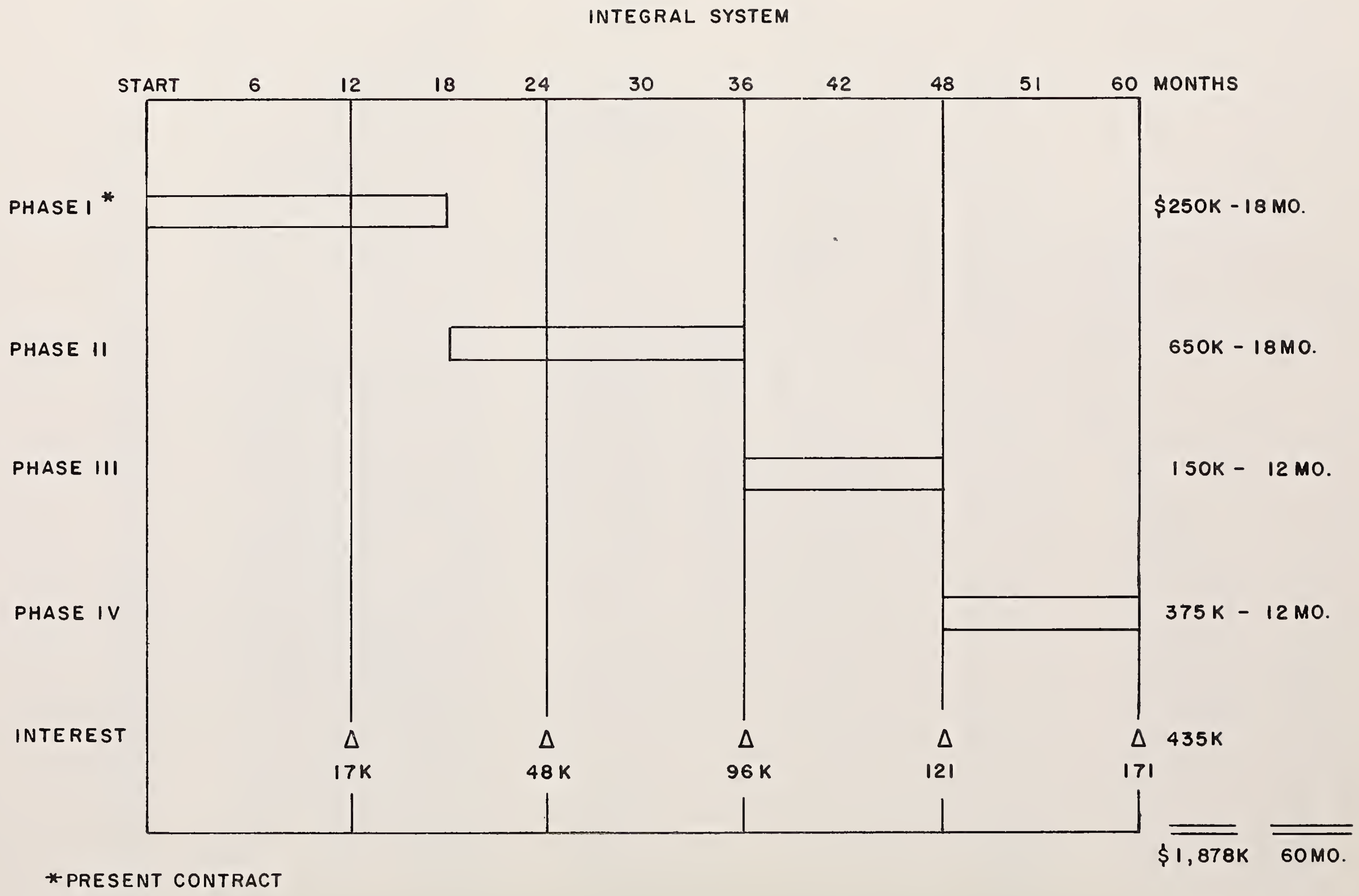


Figure 18. Projected schedule and summary of estimated costs for development of proposed system.

- A 10-year operational life
- A 50% utilization factor
- Three traverses per hole
- An average traverse speed of 10 ft/min. (3.05 m/min.)
- A 40-hour week.

These assumptions lead to a useful life of the system of approximately two million linear feet of hole. Thus, the development costs of approximately $1.9M can be amortized at $0.95/foot ($3.11/m).

The breakdown of the operations and maintenance costs (O&M) is given in Table 8. The maintenance cost is figured to be 20% of the replacement cost for the system. System replacement is estimated to be $250,000.

The cost of performing the field operation would be the amortization costs, O&M costs, and a contingency cost estimated to be approximately 20% of the amortization and O&M costs. In summary, this gives:

• Amortization costs	$0.95/ft ($3.12/m)
• O&M costs	$1.23/ft ($4.03/m)
SUBTOTAL	$2.18/ft ($7.15/m)
• Contingency (storm damage and delay, retrieval, etc.)	$0.44/ft ($1.43/m)
TOTAL	$2.62/ft ($8.98/m)

Hence, it would cost $2.62/ft ($8.98/m) to survey, or log the borehole and acquire data for later in-depth analysis.

Table 8.

O&M costs for integral system.

1. 4 operators - 6 hours per day on operations plus 2 hours on support work for 4x48 hour week- = 192 hrs/wk

   At $8 per hour plus 30% average indirect costs - = $2000/wk

   Assuming 2 weeks to complete work for three traversals in a 10,000-foot borehole, direct labor would cost $\frac{\$2000 \times 2}{10{,}000 \text{ ft.}}$ = $0.40/ft. ($1.31/m)

2. Housing and Subsistence - 4x7x$40/day avg. = $1120/wk
   $0.22/ft.
   ($0.72/m)

3. Field Engineering Support - - - - - - - - - = $0.10/ft. ($0.33/m)

4. Other operational costs:
   (Excluding highly variable support costs related to site locations) utilities, communications, security and consummables totaling $500/wk - - - - - - - - - = $0.10/ft ($0.33/m)

5. Home office overhead at about 40% of direct labor costs - - - - - - - - - - - - - = $0.16/ft ($0.52/m)

6. Annual maintenance - $50,000/yr. This will be averaged over 20 boreholes at 10,000 feet each. Hence, annual maintenance in cost per foot is:

   $50,000/200,000 ft. - - = $0.25/ft. ($0.82/m)

TOTAL = $1.23/ft. ($4.03/m)

The next major cost for the system is the data processing cost. This cost is for the non-real-time in-depth computer processing performed for the analysis and display. In order to get an idea of the amount of data possible, consider the following estimate for either the acoustic or EM system:

- 2000 samples/recorded signal x 10 bits/sample = $2\text{x}10^4$ bits/recorded signal
- 4 x 324 recorded signals/station x 10,000/0.5 stations/borehole = $26\text{x}10^6$ recorded signals/borehole (A five-degree circumferential resolving power from 90-degree receivers requires a redundancy of $(90/5)^2 = 324$)
- Therefore, $2\text{x}10^4$ bits/signal x $26\text{x}10^6$ signals/borehole - $5.2\text{x}10^{11}$ bits/borehole.

The minimum number of data bits that would be obtained from the borehole for either the acoustic or electromagnetic radar system is thus $5.2\text{x}10^{11}$ bits. It is assumed that the resistivity system would require about 10% of the number of bits of either of these, or about $0.5\text{x}10^{11}$ bits. This gives an approximate number of $1.09\text{x}10^{12}$ data bits from the borehole. Using the assumption of a 10,000-foot (3.0480 km) hole yields $1.09\text{x}10^2$ megabits/foot ($3.58\text{x}10^2$) megabits/m).

The cost of in-depth computer processing of the data, based on previous experience in computer processing of acoustical data, is estimated to be $2.50/mega-bit. This is exclusive of the costs of data acquisition or of real-time processing and display performed in the field to provide a quick-look capability for the operators.

On the basis of the costs shown above, it is obvious that it would be impractical to process all the data obtained. In order to reduce the costs, two things can be done. First, the field operators will screen the total data and select 5% of it as data for in-depth processing. Secondly, it is possible to use the computation power of the Field Data Control (FDCC) during the off hours to perform the majority of the processing. If 90% of the in-depth processing is done in the FDCC, then the total amount of off-site processing is reduced to 0.5% of the original amount of data. The costs for such a system are:

On-site processing (2 operators, 8 hours/day+expenses) = $0.28/ft ($0.93/m)

Remote site processing = $1.38/ft ($4.53/m)

TOTAL $1.66/ft ($5.46/m)

No attempt is made here to estimate the cost benefits. However, once the system has been proven and gains user acceptance, it should contribute significantly to faster, more efficient, and safer tunnel construction with attendant reduction in construction costs. It is noted that the major cost factor in using the system is the operating cost. It is conceivable that, as the system is tested and operated, system improvements will be made. With these improvements and the experience gained in signal processing and analysis, the operating costs can be significantly reduced.

6.5 RISK ANALYSIS FOR CANDIDATE SYSTEM CONCEPTS

The technological decisions which govern the outcome of the program present difficult choices. If the decisions are too conservative, the eventual system will probably operate but will not advance the state-of-the-art. This type of development is fine but, in general, does not warrant a large research contract and could be left to normal industrial evolution. Conversely, if most of the technological decisions push the state-of-the-art, the cumulative result can be a system that has a low probability of becoming operable in a reasonable time. Since either extreme is unacceptable, it is necessary to describe the system so as to maximize the probability of success.

Consider a system which requires the resolution of four independent technological problems for success. The probability that the system will be successful is the product of the individual probabilities of success, i.e.,

$$P_s = (P_{s1})(P_{s2})(P_{s3})(P_{s4})$$

where

P_s = Probability of success;

$P_{s1} \ldots P_{s4}$ = The probability of success of each individual problem.

If the individual probabilities for success are high, say 0.95, then the resultant probability of success is

$$P_s = (0.95)^4 = 0.81$$

This is good. If the individual probabilities for success are not high but still good, say 0.75, then the probability of success is

$$P_s = (0.75)^4 = 0.32$$

This is poor. This simple illustration shows that the more complex the system, the less chance for success a program will have which makes a contribution to the state-of-the-art.

To overcome this difficulty, the program should be structured and the equipment selected so that alternative options can be retained. Assume that the program described above had available two independent alternative approaches for each of the four problem areas. If the program retains the ability to exploit either approach in each problem area, then:

$$P_s = (1-P_{f1})(1-P_{f2})(1-P_{f3})(1-P_{f4})$$

where

P_{f1} = The probability of failure of problem area 1.

The probability of failure as used above is given by:

$$P_{f1} = (1-P_{s11})(1-P_{s12})$$

where

P_{s11} = Probability of success of the first alternative

P_{s12} = Probability of success of the second alternative

If, as in the first example above, we let the possibility of all events be equal, $P_{sij} = 0.95$ then

$$P_s = [1-(0.05)^2]^4 = 0.99$$

This is excellent. If the probability of success of the individual events is $P_{sij} = 0.75$, then

$$P_s = [1-(0.25)^2]^4 = 0.77$$

This is good. Thus, the ability to retain options throughout the program results in raising a marginal program to a very good program.

It is this type of restructuring that was accomplished by going to the modular concept for the system. Each of the major components:

- Acoustic System
- Electromagnetic Radar
- Electrical Resistivity
- Data Display

is described as an independent system. Each is capable of being designed and built independently of the others. This concept requires a very careful design of the interfaces since each system will be required to be connected to the same interface. It also implies that some redundancy will exist in the final system. That is, if all devices were designed as an integral system, certain reductions (e.g. power supplies, data transmission, etc.) might be available. However, in the end the modular system will be the one with greatest probability of success. Because of its simpler concepts, it can be field tested earlier and improvements to the individual system can be made as required independent of the rest of the systems.

6.6 COST-EFFECTIVENESS CONSIDERATIONS FOR PROPULSION AND PENETRATION

An alternative to the development of a propulsion and penetration unit is to conduct the geophysical survey immediately after the hole is drilled. With this approach, it is possible to use a drill rig as the propulsion and penetration device. This is attractive on the basis of low initial investment. However, operational costs will be high.

The standby charges on equipment to drill a 6-3/4 inch (17 cm) horizontal hole to depths of 1,000 (304.8 m) to 2,500 feet (762.0 m) will be high. A recent borehole cost study [ ] indicates that these costs will be on the order of $1,750 per day. At this rate, it is necessary to have complete coordination between the drill crew and the survey crew.

A second more flexible approach is to purchase a light-duty, dedicated drill rig to go with the system as part of its normal equipment. This rig could provide the propulsion and light-duty clean up of minor blockages of the hole. The cost for such a rig (e.g., Longyear 24 or Acker "Ace") with drill rod and compressor would be about $18,000.

This would imply that the system would reach a breakeven point with respect to the drill rig standby after about 12 days of operation. This approach would not only be cost-effective, but it would also add to the system flexibility. It would enable the system to operate as a functional entity, without the necessity of coordination with the drilling contractor, and the associated management problems and delays.

6.7 COST-BENEFIT CONSIDERATIONS FOR THE MODULAR SYSTEM

The purpose of this section is to present a modular approach to system configuration which will allow a low-risk, inexpensive system to be fielded early with a high probability of success. The system will have an initial capability less than the integral system but still in excess of current needs of the system users. Moreover, it will be designed such that it will be completely compatible with "add-on" modules for future growth.

6.7.1 SYSTEM CHARACTERISTICS

The characteristics of the proposed modular configuration are summarized in Table 9, together with those of the original integral system. Some of the main elements of the system are discussed below.

6.7.1.1 Propulsion and Penetration

During the first year of operation of the modular system, the propulsion and penetration will be furnished by a drill rig. After the first year of operation, the system would be provided with its own propulsion and penetration modules that would provide locomotion up to two miles (3.2 km) in 2,500-feet (762.0 m) stages. The state-of-the-art of horizontal drilling is on the order of 2,500 feet (762.0 m). The major difference for the sensor system between the 2,500 feet (762.0 m) capability and the 10,000 feet (3048.0 m) requirement is in the weight of the umbilical and the higher operational penalty for a subsystem failure. At such time when boreholes longer than 2,500 feet (762.0 m) are normally available, propulsion units would be fabricated and attached to provide the thrust.

6.7.1.2 Acoustic Transducer

In the modular approach, state-of-the-art transducers are specified. However, both the physical package and interfaces are designed to accept the higher power of future transducers. Currently available transducers have demonstrated adequate frequency response and resolution to ranges on the order of 25 feet (7.6 m) with possibilities out to 100 feet (30.5 m) in good rock conditions. To reach full range over a span of rock types will require much higher power. Transducers of this type (e.g. spark generators in fluid-filled cells) are being developed but are not proven.

6.7.1.3 Sensing Resolution

The state-of-the-art will provide approximately 90° aximuthal resolution of 6-3/4 inch (17 cm) boreholes. This is adequate

Table 9.
Summary of system characteristics.

SYSTEM CHARACTERISTIC	DESIGN OPTION	
	MODULAR SYSTEM	INTEGRAL SYSTEM
Traversing Mode	Drill Rig/Umbilical	2 mi. (3.2 km)
Self-Propulsion Capability	None (push w/drill stem)	
Traversing Capability	Limited only by umbilical	
Penetrator	None (use drill rig)	Yes
Borehole Size	6-3/4 in. (17 cm)	Unlimited
SENSING CAPABILITY		
- Acoustic Range	100 ft. (30.5 m)	100 ft. (30.5 m)
- Acoustic Radial Resol.	90°	5°
- EM Range	100 ft. (30.5 m)	100 ft. (30.5 m)
- EM Resolution	180°	5°
- Resistivity	Off-the-shelf	New development
- No. of sensing units per downhole traverse	1 or more module(s)	3 (integral)
Field Data Control Center & Surface Control	traverse control by drill rig; analog recording and graphic display at surface	Full capability unit for control, recording and preprocessing as required
Data Processing	Off-line	On-line as required otherwise off-line

for the foreseeable immediate requirement. Added resolution can be achieved by redundant computation with modification of computer software. However, full 5° resolution will require approximately 324 times the data along with modifications to both acoustic and EM radars. These modifications are anticipated in the interface designs and specifications. The actual modifications would not be provided until user demand creates the need for them.

6.7.1.4 Data Recording and Processing

During the first year of operation, the system will be operated with an on-site recording capability limited to an analog tape recorder and a conventional facsimile-type graphic recorder to provide real-time monitoring of the sensing operations. Data processing during the first year will be limited to off-line processing at a central facility. More elaborate recording and processing capabilities will be specified after the required experience with the system has been obtained and the specific cost-benefit data has been defined.

6.7.2 COST-BENEFIT CONSIDERATIONS

A reevaluation of the economic analysis of the system has been accomplished. There are total cost advantages as well as increased cost effectiveness obtained in using the modular approach.

6.7.2.1 Development Cost and Schedule

There is a net savings in development costs achieved through reapportionment of functions. Table 10 summarizes the preliminary estimates of the developmental cost impact on the overall system. Figure 19 depicts the same information in a time-phased schedule. Note that the revised estimated development time for the overall system requires 42 months instead of 60.

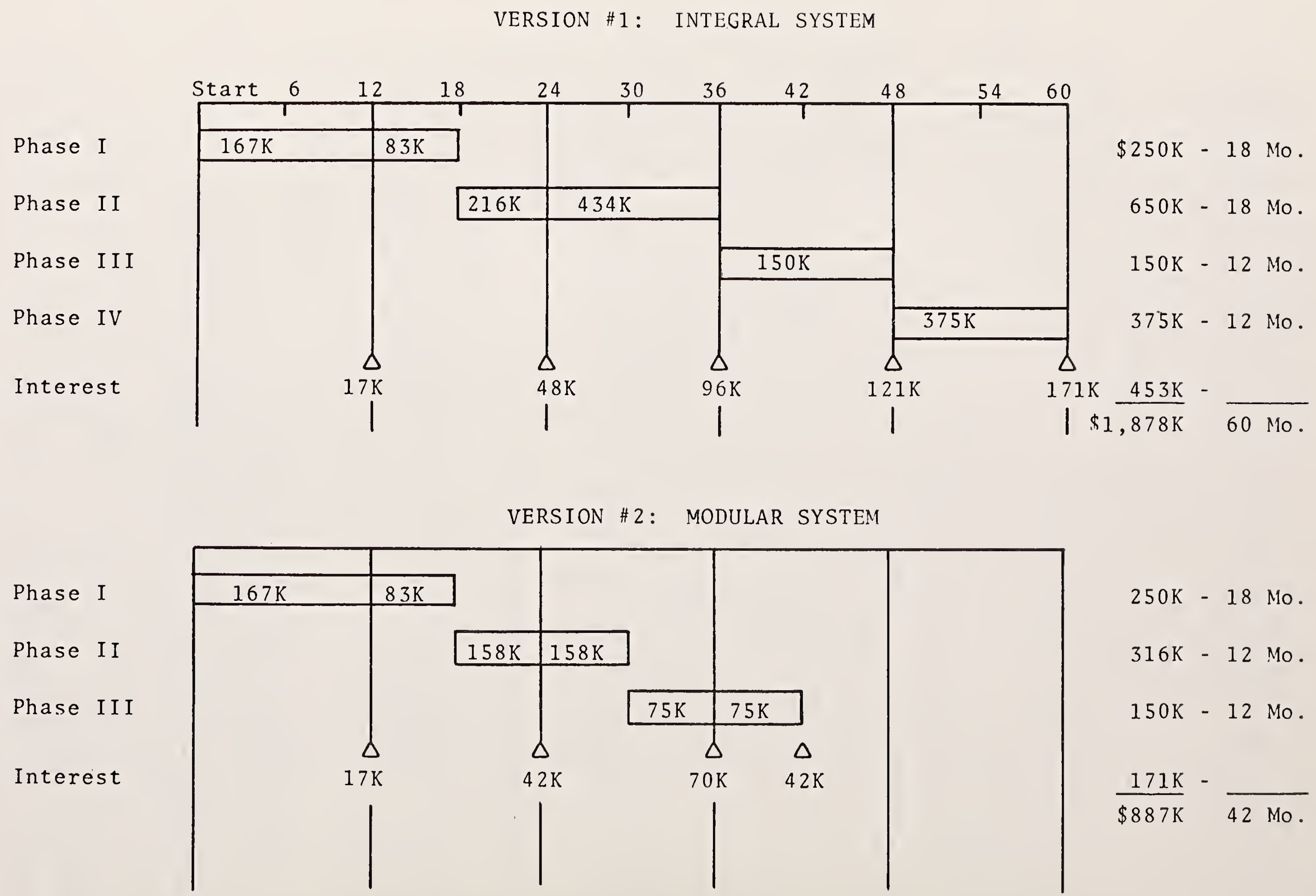


Figure 19. Projected schedule and summary of estimated costs for development of proposed system.

Table 10.
Development cost impact.

	Integral	Modular
Phase I - Feasibility Study and Design*------	$250K	$250K
Phase II - Prototype Fabrication and Test----	650K	316K
Phase III - Field Test and Evaluation--------	150K	150K
Phase IV - Fabrication of Operational Model--	375K	--
Subtotal---	$1,425K	$716K
Interest---	453K	171K
TOTAL------	$1,878K	$887K

*this contract

The modular system prototype, because it is a simpler system and has no conveyance or penetrator units, will cost about half of the full-capability version. Because of the lower technical risk, the prototype now becomes the operational model. The net result is a decrease in development time from 60 to 42 months and costs from $1.9 million to $0.9 million. The major savings of developmental dollars occurs in the Prototype Fabrication and Test phase, and in the Fabrication of the Operational Model.

The field test phase should now aim at the transition of the developmental equipment to field use. Thus, especially since this is a simpler system, operational dollars should absorb a portion of the costs at an earlier point in the program.

Since the prototype will become the first operational model and the modular system will consist of state-of-the-art equipment, only a minimal amount of developmental dollars should be required to upgrade the first operational model into its final form. The bulk of later development and modular changes will probably be justified by, and financed through, operational demand based on experience in the field.

6.7.2.2 Operational Costs

Preliminary analyses indicate that the initial operational costs of the proposed modular system will be drastically reduced. O&M costs reduce from $1.23 ($4.03/m) to less than $1.00 per foot ($3.28/m), using the same basis for the estimate. These savings result from the following:

- Higher transit speeds during survey: assumed to increase from 10 ft./min. to 40 ft./min. (3m/min. to 12 m/min.) (average). This is achieved by reduced quantity of total data collected, because of the reduced redundancy of data required. This reflects in shorter on-site times and reduced personnel and support costs.
- Reduced maintenance and contingency costs due to the lower maintenance costs of the equipment, and the higher reliability of the unit.

By strict application of the data scaling factors, data processing costs could theoretically drop from $1.58/ft. ($5.18/m) to something in the order of $0.58/ft. ($0.16/m). The probable result, however, would be some significant reduction in data processing costs and a significant increase in the percentage of each hole over which these costs are amortized. In other words, with high data processing costs, only a small portion of each hole would receive deep processing. With the costs reduced several orders of magnitude, a much larger percentage would be surveyed and processed.

6.7.3 SUMMARY AND CONCLUSIONS

This system will be one which will take maximum advantage of the best of today's technology. It will equal or exceed the user's knowledge of how to exploit its full capability in today's economic environment. It will be designed to grow with the user's growth in sophistication in the application of the data it provides to reduce tunneling costs. The user's operation will become increasingly more cost competitive as he develops in his ability to use the system effecitvely.

The program will be accomplished at an increased level of cost effectiveness compared to the original concept. Development costs will be reduced and the development cycle shortened. In addition, there will be a drastic reduction in the projected operational cost on a cost-per-foot (m) basis.

7. PROTOTYPE SYSTEM SPECIFICATION AND DESCRIPTION

7.1 DISCUSSION OF THE SPECIFICATION

A specification is a formalized communications document which can exist in many levels of detail. It is prepared at the conclusion of any specific phase of a development program. Its purpose is to define a system in sufficient detail so that the next phase in the orderly developmental cycle can be initiated. It should be possible for follow-on work to be performed by personnel unfamiliar with the preceding program background, without the necessity of reaccomplishing and repeating the work done to that point in the developmental cycle. The specification should provide the information and the data necessary to begin the next logical sequence in development, manufacture, or test. A specification which is incomplete necessitates wasteful repeat of prior efforts. Conversely, a specification which overspecifies can be even more dangerous. It ties the hands and usurps the logical and necessary prerogatives of the personnel who will be performing the next phase of the program.

There are three general types of specifications: performance, functional, and detailed design. Any one of these can constitute a satisfactory procurement specification. Actually, there are no clear-cut lines of demarcation between these three types of specifications. One gradually transitions from one into another in orderly sequence of the developmental cycle. However, it should be remembered that, even though the transition is gradual, the end points of these specifications are generally mutually exclusive. It is possible and reasonable to specify the performance requirements which a system must meet. It is also possible and reasonable to specify in detail how the system shall be designed. It is neither possible nor reasonable to specify on an apriori basis that a new piece of equipment or a system designed according to a preconceived detailed specification shall meet a preconceived level of performance. Although this is the goal of any developmental program, it can only be achieved after the first article designed according to a detailed specification has been fabricated and thoroughly tested under the operational environment in which the system must operate. Only then is it possible to specify both detail and performance for future procurements.

The specification developed as a result of this program is functional. It is intermediate between the pure performance and the detailed design specifications. It defines the system and its associated subsystems to a series of individual levels where added work, beyond the scope of this effort, is needed before a detailed design document can be prepared. In general, the added work which will be required is in the form of physical assembly of functioning hardware and subsystems. These should then be tested in a real or simulated environment to insure their operational function and their fit within the tight confines of a borehole package.

Every effort has been made to bring the total system specification to a consistent level of functional detail without trying the hands of the designer who must pick up at this point and design and test breadboard or brassboard type of hardware.

7.2 PERFORMANCE OBJECTIVES

7.2.1 NEAR-TERM OBJECTIVES

The system being developed under this program involves the integration of a number of concepts which have never been tested previously or at least have been subjected to no more than cursory proof-of-performance type of measurements. Thus, while the functional and operational objectives of the program have not been forgotten, the near-term objectives of the prototype system as specified place heavy emphasis upon providing a system which will resolve technological indeterminacies and provide hard field data as a basis for future design and growth. Every effort has been made to insure that the prototype system, when fabricated and fielded, will provide valuable and useful data to fulfill its operational goals and meet the needs of the tunneling industry. However, these near-term objectives will be those operational advances which can be achieved by incorporating only those techniques which are either within the state-of-the-art or will require at most a modest improvement in what is already available. The system, as specified, will enable future designers to concentrate on those few critical areas where intensive design and development will be needed.

7.2.2 FUTURE OBJECTIVES

The ultimate goal of this system is to provide a tool which will meet, on an economical, cost-effective basis, the total requirements set forth in the contract. In order to accomplish this, the system is specified as a group of modular assemblies and subassemblies which are designed for individual replacement. This would be by like items with improved capabilities as subsequent collateral advances in the state-of-the-art, and operational experience, indicates the need for improvements in these specific areas. The rest of the system and the interfaces involved are so specified that these improvements can be incorporated with minimal impact and without the need for complete system redesign each time a modular improvement is incorporated.

7.3 OPERATIONAL SCENARIO

In developing the prototype system specification, it is necessary to keep many factors in mind. In addition to the technical, economic, and operational goals which have been defined during the course of this program, it is necessary to consider the physical methods by which the system will be deployed, the data to be gathered, and the final processing to be accomplished. Operational procedures for using the system can only be truly developed on the basis of experience which is gained through use of the system. However, in order to keep the problems of deployment in focus, an operational scenario must be prepared to insure that the system can be successfully operated by available personnel within the physical environment in which it must be deployed. This operational scenario simply consists of a number of assumptions and logical deductions expressed in narrative form to help envision the problems which might be encountered by a system built to meet the specifications of this program.

7.3.1 PLANNING

It is safe to assume that, for the foreseeable future, each new horizontal borehole to be surveyed will constitute a new and unique problem. Long before the borehole itself is even drilled, considerable planning, site survey, and geological investigations will have been performed. On the basis of this data, a drilling schedule will be established and the drilling of the borehole initiated. If the drill rig is to be used as the mechanism for propelling the survey package into the hole, close coordination must be maintained between the drilling progress and survey personnel. The timing of the survey operation must be programmed to coincide with the completion of the borehole, otherwise excessive standby costs for the drill rig and drill crew would be incurred. During the drilling operation, a measurement projection document should be prepared. This would be based upon all available geotechnical information, evaluation of the types of geologic structures which will be of interest, projected hazards which might be expected, the type of tunneling to be performed, and the informational needs of the geotechnical planners, and tunnel designers. From this document the technical crew will determine what particular measurements will be needed, the sequence in which they are to be taken, and the amount and type of data to be collected at various locations within the borehole. The tests will be planned to achieve a dual goal. The operational needs of the program will receive first consideration. However, one of the fundamental goals of the prototype system is to gather data upon which to base further improvements. Thus, the test planning will include specific tests aimed at adding to the available fund of knowledge. The tests would include collection of data system and component performance as well as the basic characteristics of the environment in which the hole exists. Data for the study signatures of generic classes of hazards and geologic structure will be collected.

7.3.2 MEASUREMENTS

The first phase in the actual subsurface measurement program is mobilization. This should begin several days before the scheduled completion of the borehole. The equipment and crew will be at the drill site. They will collect critical information from the driller's log, such as the various rock types encountered, location and orientation of deviations within the hole, locations of forks or multiple holes, any known hazards such as dangerous key seat areas, or areas where there is danger of hole collapse. The draw works must be unloaded and located with proper orientation with respect to work areas and the hole. Any shoring, site leveling, bulldozing, and necessary physical housekeeping functions must be performed in order for the measurement program to begin with the minimum possible delay upon the completion of the hole.

When the same drill rig which was used to drill the hole will also provide the propulsion for the downhole package, the data collection phase must begin as soon as possible after the hole has been accepted and released for operational use. The measurement procedure will consist of mounting the selected sensor package on the down hole interface, which in turn is mounted to the front of the drill string. The nose cone package will be mounted in the front to lead the total measurement system assembly into the hole. The package will be propelled by the drill rig to the bottom of the hole, whereupon it will either be released from the drill string and drawn out by the umbilical or alternatively the drill string itself may be used to remove it from the hole. Measurements will be made only as the package is withdrawn from the hole. This procedure has been selected because much more precise control of the location at which measurements are taken can be achieved while either the drill string or the umbilical is in tension than while the package is being shoved into the hole. In addition, operating with the umbilical in tension enables the use of standard separation units, which are defined in the specification, to separate packages and elements within the packages. This would otherwise be difficult and cumbersome to accomplish.

The first measurement to be made will be with the electromagnetic radar. This will consist of a rapid continuous scan along the length of the borehole. This data will be printed out for quick-look, on-site evaluation as it is being taken. A preliminary interpretation and correlation with the projected data from the premeasurement plan and available core data will be made. Modifications to the survey plan may be made on the basis of this data.

The next probe to be deployed will be the resistivity probe. This probe serves two major functions:

- It will take conventional resistivity data which has been shown to have high correlation with rock strength characteristics.
- It will take relatively crude data with considerable penetration into the surrounding rock to provide gross warning information, indicating zones where there will be marked changes in resistivity at distances from the borehole

> which may not be obvious in either the core data, or the radar data These zones will be marked for extra attention in the subsequent data collection, reduction, and interpretation processes.

On the basis of the available radar and resistivity data, the measurement program for both subsequent radar data collection and the measurements to be made with the acoustic probe will be refined. Because the use of the acoustic probe will be a slow operation at best, it is anticipated that detailed acoustic data collection will be limited to only selected portions of the borehole where supporting data indicate that detailed acoustic evaluation will be of value. Thus, it is anticipated that the acoustic probe will be the last one run into the hole. Detailed data on close spacings will be taken where required with additional data in a reconnaissance mode taken at reasonable separation intervals along the hole.

Finally, all data taken at the site will be reevaluated to determine if there are any indications of anomalous structure which might warrant the use of special data collection techniques or rerun of the data collection under different controlled conditions, such as differing separations between the acoustic transmitter and receiver.

Contingency support will be available during the data collection process. This will include the availability of the large drill in the event the hole collapses or clogs during the data collection process. Alternatively, the light-duty drill rig will be available when the large rig is no longer on site. A limited group of fishing tools will be available as part of the overall system package in the event of a jammed package in the hole.

All data taken will be collected on magnetic tape along with any voice comments of the operator, a record of any malfunction which occurred, and any other pertinent data which can be stored on the tape. This will be accompanied by the test operator's log which describes any ancillary data not on the tape. It also annotates any special measurements which were run, their purpose, their approximate location on the tape. It provides additional information which would be of value in the data processing center as an aid to extracting additional information from the user of advanced data processing techniques.

At the completion of the data taping phase, the operation must be demobilized. Aside from the normal procedures of cleaning the equipment, performing any preventive maintenance, repacking and leaving the site, the work involved in demobilization will vary from site to site. As a minimum, the site must be left in a safe, standby condition ready for the next operation in the tunneling process.

7.3.3 DATA HANDLING AND PROCESSING

Initially, the test operator, or the lead geophysicist who performs the measurements, must also be expected to take the lead in the data processing operation. This is not to imply that he must be a data processing specialist. However, he must be competent to work with the data processors to identify the particular zones of interest and the features which he wants to see enhanced within the data. Work on ancillary programs has shown that, for the foreseeable future at least, it will not be feasible to automate the data processing entirely. Just as each survey site will be a different geotechnical problem, the data from that site will be a different data reduction problem. What processes have the maximum payoff for what particular situation can only be learned by experience. Thus, it must be anticipated that the person who took the data, who knew the conditions under which it was recorded, who knew the reasons for performing specific tests in specific manners, must be in a position to follow this data through the processing and interpretational cycle. For this reason, the specification has been written in such a manner that the maximum amount of potentially valuable information is recorded in an automatic or semi-automatic manner on the tape in the field. Even with these aids, the memory and the knowledge of the lead geophysicist will be needed to correlate all of this data into a meaningful interpretation.

7.4 EVOLUTION OF PROTOTYPE SYSTEM SPECIFICATIONS

7.4.1 BASELINE SYSTEM

The development of this prototype specification is a continuing evolutionary process. It started with the performance specifications of the contract and was carried through the functional analysis to establish a preliminary baseline system. The preliminary baseline system was used as a focal point upon which to refine and concentrate design and developmental studies. This eventually evolved into a second baseline system which was presented at the Preliminary Design Review. Photographs of scale models are shown in Figures 20 and 21. Subsequent to this, the evaluation of the many nontechnical restraints, which the total program had to meet, led to a simpler approach than was defined by the second baseline system which in turn had evolved to meet the total system requirements, both long and short range, in a single system. The simpler approach which evolved was called the modular system. It incorporated the major features of the baseline system but recognized that the total development could best be broken into smaller, time-sequenced programs.

7.4.2 MODULAR APPROACH

The modular approach which evolved was based upon the realistic

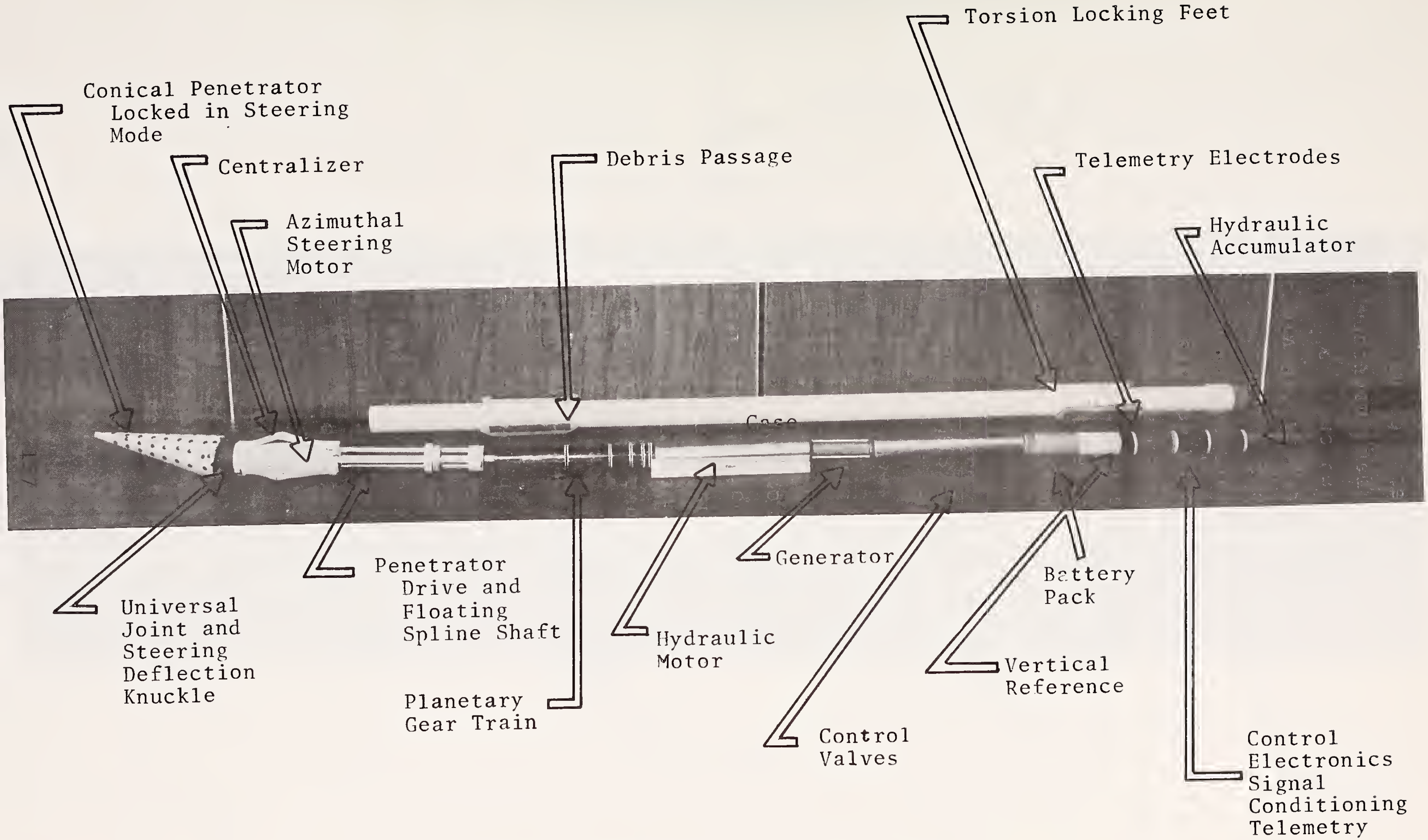


Figure 20. Exploded view of penetrator model.

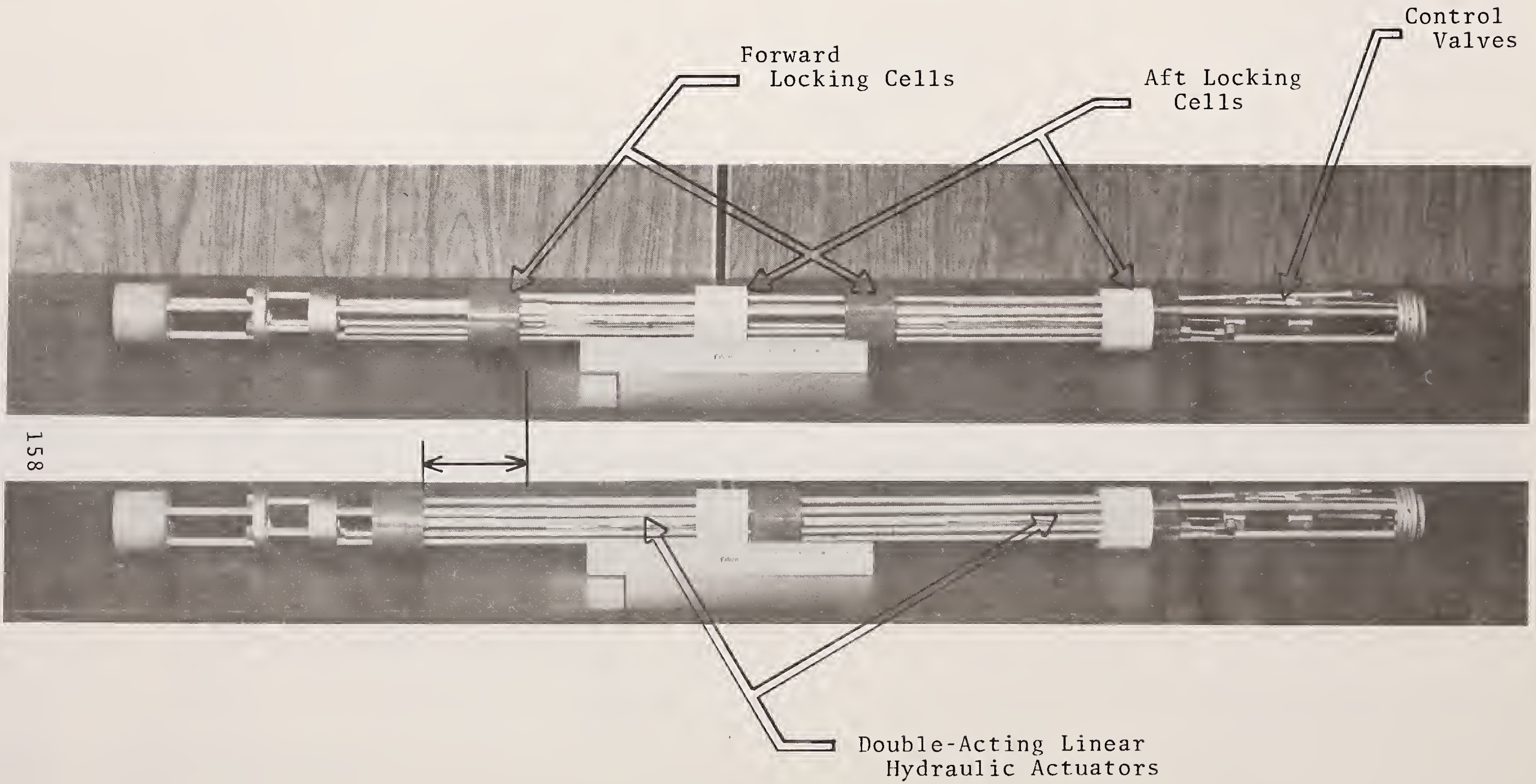


Figure 21. Propulsion unit showing linear displacement of locking cells.

appraisal of the total program. This included recognizing that it was beyond the state-of-the-art to drill 10,000-foot (3048.0 m) boreholes and probably will be so for a considerable length of time. Thus, the modular system was defined around the concept of using shorter boreholes in the range of several thousand feet. The original concept was that the system would be almost identical to that proposed in the second baseline system, except that the propulsion and penetration unit would be deleted and a drill rig would be used for this purpose. It was to be designed in a modular manner so that, at such a time as the increase in drilling capability warranted, a self-contained in-hole thruster could be added as a modular unit without major redesign. The modular approach was refined still further on the basis of the risk analysis which showed that the developmental risks of trying to push the state-of-the-art too far in too many areas were becoming excessively high. This was true even though the developments required when viewed individually did not involve an excessive risk by themselves. From this, the total concept of the modular prototype evolved.

7.4.3 MODULAR PROTOTYPE

The modular prototype system is the one defined during this contract. The specification for this prototype system appears in a separate contract deliverable document entitled, "Detailed System Design Specifications and Drawings for Prototype System." Since the specification is a functional and not a detailed design specification, it is subject to change as knowledge grows during subsequent design and fabrication stages. Thus, the specification which has evolved as a result of this total program is actually the final evolution of the baseline system itself, presented in specification format along with the accumulation of design parameters defining the envelope in which this final baseline system must function. The modular prototype system as specified represents the best state of firm knowledge of how the system could be fabricated as it exists as a result of this program. In many areas, the concepts are quite firm and well developed. Other areas of the specification are much softer, needing additional data from either test or design experimentation before they can be carried to an equivalent degree of completion. However, regardless of the degree of completion of the individual specifications of the units, the modular prototype concept has been carried through. In each case, the interfaces have been specified so that they are common. A particular subunit involved can be designed and inserted to meet these interfaces in such a manner that the rest of the system and its progress in design need not be hampered in its development by the programs necessary to bring these soft areas into fruition. For example, the acoustic subsystem and the resistivity package can be designed and even fielded and tested without being hindered by the need to develop directional borehole radar antennas in support of the radar subsystem. By structuring the specification in this manner, the greatest freedom, not only for future system growth but also for system development, is provided.

7.5 PROTOTYPE SYSTEM SPECIFICATION

The prototype system is specified in detail in the separate contract deliverable mentioned above. Only the essential features will be summarized in this discussion.

The functional analysis for this program identified six major subsystem areas which comprise the total horizontal borehole sensor system. Subsequent work has identified that the Data-to-Information-Conversion Center and the Information Display Center are functionally procedural utilizations of available computational facilities. As such, they are not covered in the specification. The specification does take steps to insure that the information collected by the prototype modular system is compatible at the interface between the field system and the computational center.

The system as defined by the specification is a highly mobile geophysical measurement system. It is intended to operate primarily in horizontal, pre-drilled boreholes for hard rock tunnel site investigation purposes. It will be able to operate off-road under the worst of conditions, arrive at the site, set up rapidly, clean the borehole of minor blockages, and take measurements in the borehole.

Three types of sensing are specified:

- Electromagnetic radar
- Pulsed acoustic
- Multi-spaced array resistivity.

The various sensors are designed to be used in traverses along the borehole. Data will be taken and stored on magnetic tape for subsequent reduction and analysis at a computational center. Only that data necessary for making field decisions, concerning the data and measurement procedures, will be displayed and interpreted on site. The field portion of the measurement system will consist of four major subsystems:

- The Field Data Control Center in which will be collected those functions necessary for the control of the measurement process. This will include the quick-look display of the raw downhole data and the recording of this data and the conditions under which it was collected.
- The Surface Support System in which is collected all of the mechanical functions necessary in the field test operation, but peripheral to the direct measurement process.
- The Umbilical which serves as the physical link and the electrical interface between the downhole package and the surface.
- The Downhole Package in which is collected all of the functions which are performed within the confines of the borehole.

The drill rig which originally drilled the hole may remain on-site and be used to push the package into the hole. At this time, the package will be released and the drill rod removed from the hole. A light-duty drill rig will be included as part of the system, for added flexibility and resurvey of the holes when the main drill rig has been removed. The Field Data Control Center is specified to be located in a four-wheel drive utility vehicle. It will have a control console from which the test operator can remotely control all functions required in the measurement and the data collection process. It will provide him with recording and display of all pertinent information necessary for him to perform this function. This will include:

- An eight-channel analog frequency-modulated tape recorder and a graphic facsimile type recorder which has the capability of displaying both intensity-modulated and amplitude-modulated data in a facsimile type display. It will contain ample work space and data and tape storage facilities for field operation, and will be air-conditioned or heated to maintain it within the broad temperature limits of 60° to 90°F (16°-32°C).

The Surface Support system will consist of the following units:

- A four-wheel drive utility vehicle which will house the Field Data Control Center and provide for personnel, transportation, and test support functions.
- A low-body four-wheel drive trailer shown in Figure 22 will be mounted the total remaining field system for transportation as an integral unit.
- A light-duty horizontal drill rig, Longyear-24, Acker (Ace) or equivalent. This drill rig will serve a dual purpose of cleaning minor blockages from the hole and providing the propulsive function of the downhole package when the main drill used to drill the hole is not available.
- A draw works will be included for the purpose of storing and retracting the umbilical cable. It will be sized and powered with sufficient power

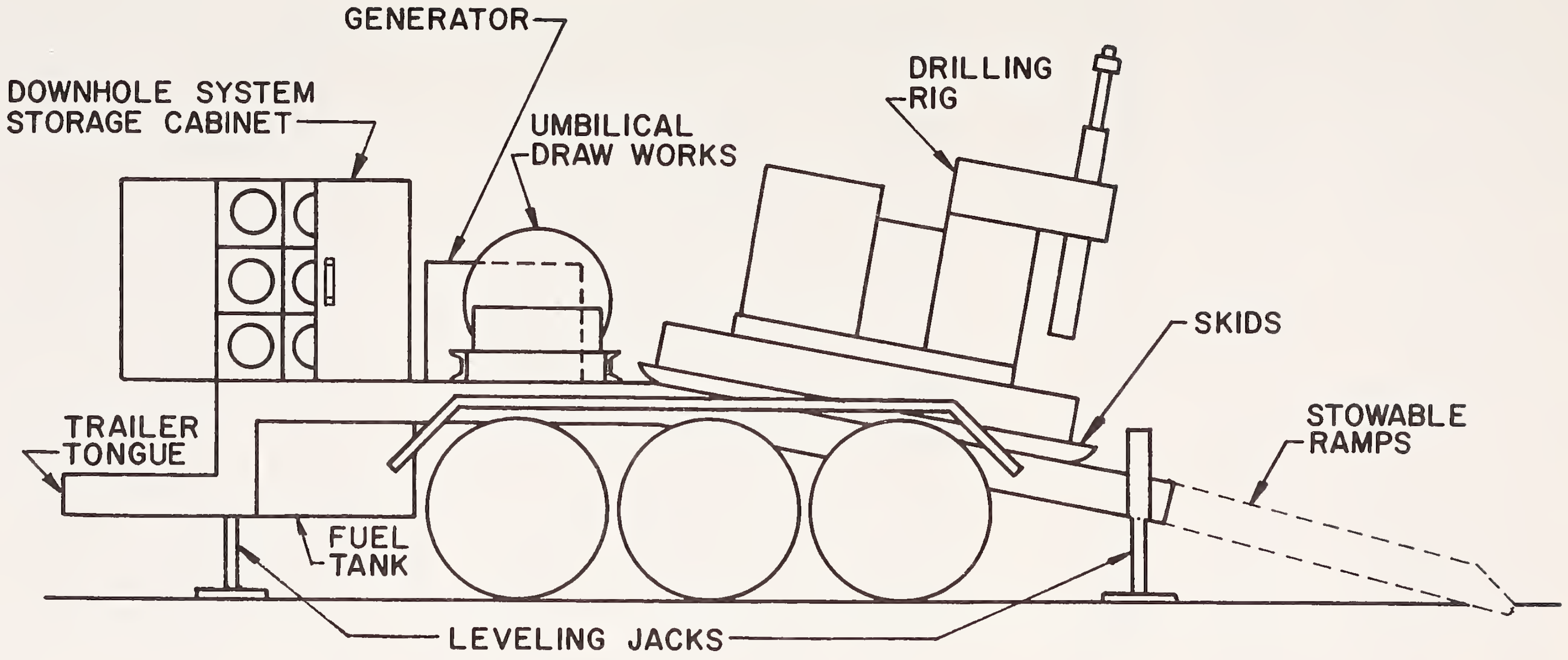


Figure 22. Surface support system trailer.

to retract the downhole package and to insure that the umbilical is always in tension. Mounted on the draw works will be an odometer device which can accurately measure the amount of cable remaining in the hole. This data will be transmitted to the control console and simultaneously recorded on the appropriate track of the tape recorder.

- A gasoline-powered generator will be included which will provide at least two kilowatts of 60-cycle power at 115 volts and one kilowatt of 60-cycle power at 230 volts.
- A strong-back assembly jig which will be used for assembling the downhole package and inserting it into the borehole.

7.5.1 THE UMBILICAL

The umbilical will be a standard well logging cable with characteristics equivalent to or exceeding the following:

- A coaxial cable member of RG178/U.
- Three lines of insulated No. 6 stranded wire, with breakdown voltage of the insulation in excess of 500 volts.
- A strength member with a tensile breaking strength in excess of 5,000 pounds (2268 Kg).
- An extruded polyurethane abrasive-resistant jacket.

7.5.2 DOWNHOLE PACKAGE

The downhole package is almost a major system by itself. Since it will absorb a disproportionate share of subsequent developmental effort, it has been specified in much greater detail than any of the other subsystems. A major feature of the downhole package is that it is assembled by fitting together a number of functionally independent subunits in the form of replaceable packages which all operate through a common interface. This common interface is referred to as the standard interface.

The standard interface shown in Figure 23 is so defined that any two functional packages may be connected together without danger of mismating in any aspect of form, fit or function. Although the downhole package as specified is intended to use a single sensor per traverse of the borehole, every effort has been made in specifying the system so as not to preclude the possibility of using multiple sensors per traverse with a minimum of system modification, should operational experience indicate the desirability and the feasibility of this approach.

The downhole package will consist of three major subunits and one minor subunit as illustrated in Figure 24. These subunits will consist of the following:

- A downhole interface package which will provide the physical interface with the drill rod and the electrical interface with the umbilical. It will also contain all functions and circuitry which are common to any of the three sensor packages which will be part of this system, as well as a common interface with these packages.

- A sensor package which is one of three separate and distinct packages to be used during any one measurement traverse of the hole. These will consist of:

  -- A pulsed electromagnetic radar sensor system.

  -- A pulsed acoustical sensor system.

  -- A multi-electrode array of resistivity probes.

  The specification of the individual sensor packages will be covered more thoroughly in subsequent paragraphs.

- A nose cone package which will contain a force sensor to warn the operator of a blockage in the hole and will be interlocked with drill rig controls in such manner that operation of the drill rig will be disabled at any time the force build up in front of the package exceeds a specified level. It will also be equipped with a deflectable steering device which will enable the operator to direct the package into the proper entrance of a forked, deviated hole.

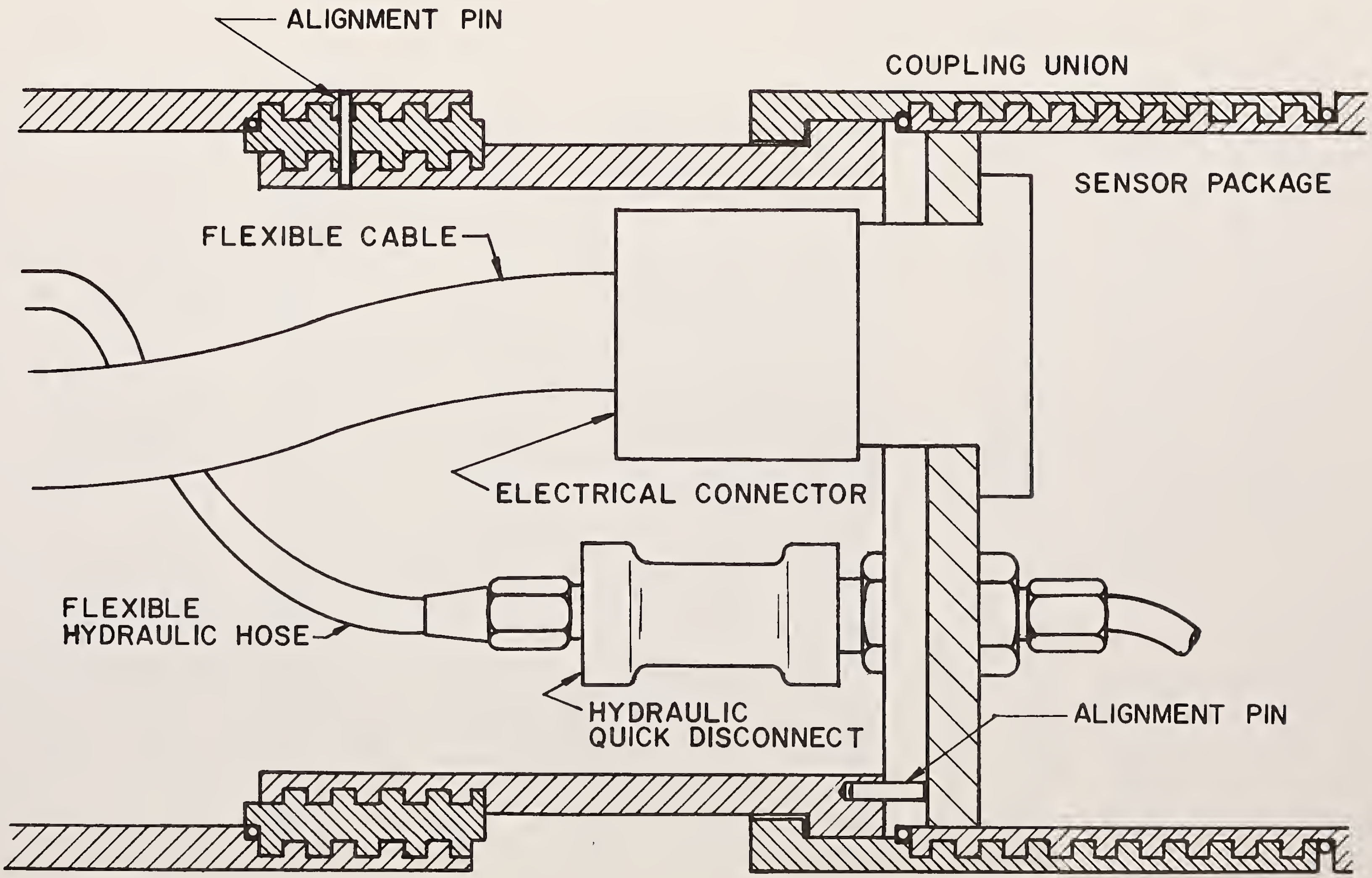


Figure 23. Conceptual drawing of downhole package interface per par 7.5.2.

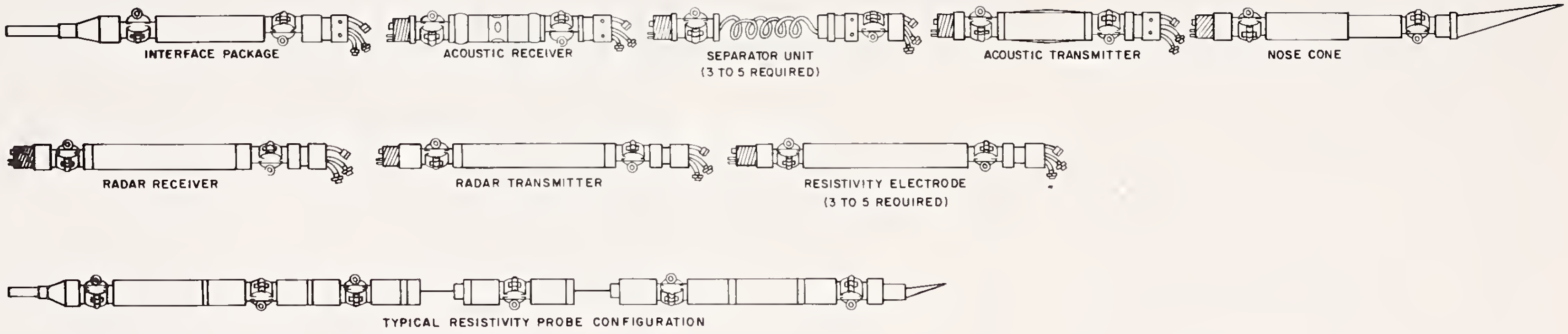


Figure 24. Modular downhole package configuration.

- The separator unit shown in Figure 25 is also specified and is considered as a minor subunit. Three to five of these units will be required in the system. It will be a form of intra-package umbilical. Its purpose is to meet the standard interfaces and to extend the separation distances between these interfaces. It will consist of a helically cast elastomeric coil containing the interfacing cables and hoses and a separate tensile strength member. It will be packaged to go downhole in a canister which will be an integral part of the downhole package. When the downhole package is withdrawn from the hole, the separator units will separate so that, on withdrawal, the packages may be separated by fixed, predetermined distances.

7.6 SENSOR SUBSYSTEM SPECIFICATIONS

7.6.1 RADAR SUBSYSTEM

Although the radar subsystem is probably one of the most important of the sensor packages, it is specified in the least detail of any of the three sensors. This is done for two reasons:

- There are at present no viable options to the specification of the radar subsystem other than to select a Geophysical Survey Systems, Inc. unit. Other organizations are involved in working with ground-probing radar; however, none of them have carried their equipment beyond what could be considered as an experimental breadboard stage. GSSI has a commercially available unit which can be repackaged to serve as the radar sensor. Thus, the only development required would be the necessary engineering and model shop work to reconfigure the radar so that it would physically package within the confines of a borehole package.

- Although studies, limited tests, and the best technological advice available indicate that it is feasible to design borehole radar antennas with broadly directive azimuthal beam characteristics, no such antenna has yet been designed or tested. Thus, before a specification can be written to include a directive antenna in this system, additional tests and experiments will have to be made

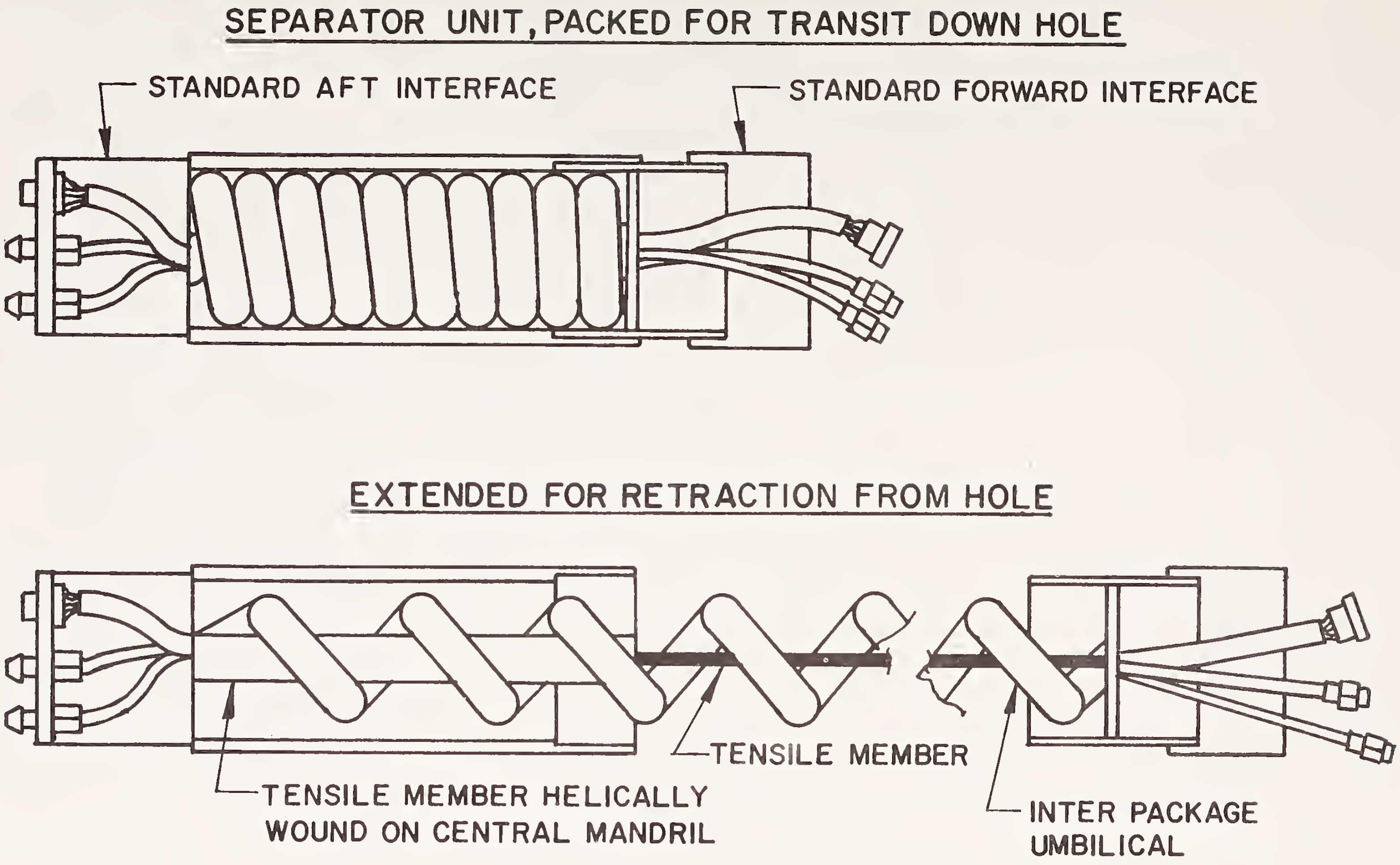


Figure 25. Separator unit for achieving fixed separation between functions.

to establish the best configuration to use. There is little that can be said in this specification about the methodology or the packaging of such an antenna. The specification limits itself to defining the functional characteristics which would be desirable for such an antenna to have. The needed follow-on developmental program is defined elsewhere in this report.

7.6.2 ACOUSTIC SENSOR SUBSYSTEM

The acoustic sensor subsystem is specified as consisting of a 90 kilowatt peak impulsive magnetostrictive source operating at a pulse repetition rate of 10 pulses per second. Four receivers are separated by a variable distance from the transmitter at 90° increments around the probe. Each receiver sensor consists of a stack of piezoceramic crystals one inch (25 mm) in diameter and 1/10th inch (2.5 mm) thick. The total number of elements used are ajusted so that the resonant frequency of the stack is between 30 kHz and 50 kHz. The output of the receivers goes to individual preamplifiers which are specified to have a 40 dB gain with a 0.05 microvolt amplifier input noise and a broad bandpass between two and 40 kHz. Variable bandpass filters are inserted between the preamplifier and the final amplifier. The final stage is an 80 dB gain logarithmic amplifier to give an overall system gain in the order of 120 dB.

Coupling of the acoustic transmitter output is through a hydraulically inflatable elastomeric sleeve which is expanded against the borehole wall by a two-stage hydraulic system. The two-stage system is so specified that the expansion and retraction of this sleeve will occur in less than one second. This is achieved by initial expansion through a low-pressure [25 psi (172 kPa)] high flow rate pressure-to-volume hydraulic converter. Final locking force to achieve firm contact between the cells and the borehole wall is achieved with a relatively slow flow rate, high-pressure [200 psi (1.38 mPa)] hydraulic source. Good acoustical contact is assured by injecting water between the outside of the elastomeric sleeve and the borehole wall just prior to applying the locking force.

Good acoustical contact for the receiving sensors is achieved by expanding outward the individual ceramic stacks, properly protected, to make physical contact with the borehole wall. This is accomplished hydraulically.

7.6.3 RESISTIVITY PROBE

As specified, the resistivity package consists of a number of individual electrodes which are assembled on site with appropriate spacing, or separation units, to configure the desired electrode array to be used for the purposes of that specified measurement. There are many potentially valuable borehole electrode arrays which can be used on this system. Thus, the resistivity package is specified as an assembly of electrodes and a resistivity probe controller package which will rapidly scan the electrodes through a number of preprogrammed array configurations. In this manner, the resistivity electrode will not only provide information concerning lateral fractures at angles too steep to be properly detected by either the radar or the acoustic sensor, but it will also provide information concerning the bulk resistivity in the vicinity of the borehole which is known to correlate quite well with the engineering characteristics and strengths of rock. By properly interpreting the returns from array configurations of ever-increasing electrode separation, it will be possible to determine changes in the bulk resistivity at depths which, when used in conjunction with information from the acoustic and the radar probes, will provide diagnostic signatures of gross changes in the surrounding geological environment which do not intersect the borehole.

7.7 DESIGN FOR FUTURE GROWTH

The specification also includes design guidelines to insure that the design of the system and its associated subsystems will be such that the total system can eventually meet the functional objectives of the overall program through modular growth, rather than by major redesign.

Packages and subunits are specified to be assembled in functional modules which can be replaced at later dates without major impact upon interfacing units.

Guidelines for identifying those particular modular units to be kept functionally independent are provided. They are based upon the state-of-the-art of that particular unit. Thus, whenever the state-of-the-art unit is available but there are readily foreseeable potential gains in the future but as yet unproven units, the state-of-the-art unit will be specified to be incorporated in the modular package. However, the interface between that unit and the rest of the system will be designed so as not to preclude the incorporation of the more advanced form of the unit at such a time as it becomes available. The specification also includes illustrative, currently foreseeable growth units which fit into this category. Design limitations are also considered. For example, the downhole package is specified to be designed so that its only limit in penetration depth shall be the length of the umbilical and the physical limitations imposed by the use of drill rigs for propulsion and hole cleaning.

Where necessary, operational procedures are identified which will insure the adequate functional fulfillment of the program goals by a system constructed according to the specifications.

8. PROTOTYPE SYSTEM PERFORMANCE EXPECTATIONS AND RECOMMENDATIONS FOR FURTHER DEVELOPMENT

8.1 PROJECTED SYSTEM PERFORMANCE

8.1.1 DISCUSSION

The expected performance of the prototype system can be defined in several ways:

- It can be projected in purely technical terms. E.g., under a specified set of conditions of attenuation of the sensor signal by the medium, a target of specified size and electrical or acoustical contract can be detected at a certain range under specified noise conditions.
- It can be projected statistically, on the basis of probably variations of the target and medium characteristics.
- It can be projected on a functional basis. Classes of targets meaningful to the user can be detected to specified degrees.

The technical method is attractive from a conceptual view. It is of little functional value for a system such as this. Rock and target characteristics can be expected to vary over such a wide range that any such specification would be almost meaningless to anyone but the technical specialist who designs the system.

The statistical method suffers in general from the same weakness. The projection can be no better than the statistics upon which it was based, and the degree to which any particular borehole environment is represented by these statistics.

The functional definitions of system performance, while much more qualitative than the other two, present a more meaningful picture of the probable performance.

8.1.2 INITIAL PERFORMANCE

The performance of the prototype system when it is initially fielded will be that which is achievable by current state-of-the-art hardware. Thus, although equipment has not been used before for this particular application, it is reasonably safe to project performance based upon hard data from performance in analogous situations.

The radar system has already demonstrated its ability to resolve targets of geological significance to ranges in the order of 40 to 50 feet (12 to 15 m). The rock involved was a hornblende-gneiss which has median loss characteristics. The range was reduced to considerably less than 25 feet (7.6 m) in chlorite schist, a very hostile material with poor structural characteristics. It would seem reasonable to project that ranges of 75 to 100 feet (23 to 30.5 m) could be achieved under the very best of circumstances. These could reduce to as low as 5 to 10 feet (1.5 to 3.0 m) in very poor rock.

The short range is actually misleading as the borehole would actually have entered the hazardous rock conditions under these conditions. Thus, the detection range would be academic. A truer projection would be that this dangerous condition would probably be detected at a median range of possibly 30 to 50 feet (9.1 to 15 m).

The resistivity probe will penetrate to depths in the order of the maximum electrode separation used. The way the probe is specified, it is a collection of electrodes which can be assembled at any desired separation. Its performance can be adjusted to meet the desires of the user. The ability of the probe to effectively resolve range remains to be proven. At present, it is only possible to project that technically it will have the capability to extract information from the vicinity of the borehole to any realistic range desired. The degree to which this information can be useful remains to be proven.

The resistivity probe differs from both the electromagnetic and acoustic radars in that it senses bulk characteristics of the medium while the other probes delineate interfaces. While the resistivity data will be much more coarse than the returns from the other two, it will be sensitive to those gross structures which will have major geotechnical impact. The radar, and to a lesser extent the acoustic probe, may see these structures but not readily identify them as uniquely important features.

Projecting the performance of the acoustic probe is more difficult than for the other two, as it has not been used extensively in the single borehole mode. Operational acoustic probes are being used in a transillumination mode between boreholes to distances of 25 to 50 feet (7.6 to 15 m). This would equate to proven ranges in the order of 15 to 25 feet (4.6 to 7.2 m). Calculations indicate that under favorable rock conditions returns from high contrast targets should be achievable to distances of 50 to 100 feet (15 to 30.5 m).

The prototype system will have limited azimuthal resolution in the radar and acoustic modes, and no azimuthal resolution in the resistivity probe. The degree of resolution can only be estimated as there is no hard experimental data available from boreholes. It is estimated that the resolution will be on the average approximately 90°. It will be better for the higher frequency components and poorer for the lower frequencies. From an operational standpoint, this would enable the location of a target to be within a given quadrant, around the axis of the borehole.

One of the major factors which has been learned during the course of this program has been that the potential users are ready to accept only limited increases in data collection capabilities.

They have established predictive procedures. Until they know how the potential results from a system such as this can be integrated with these procedures, they will be unwilling to place heavy reliance upon the data. It is believed that the output of the prototype system will provide much more data than the users will be willing to accept initially. The initial performance should be more than adequate to provide a point of departure for entering this tool into the operational inventory.

8.1.3 ULTIMATE PERFORMANCE

One of the most attractive features of the modular system as specified is that its ultimate performance is not specified and thus is not limited. It is designed for growth. Its ultimate performance can be directed to meet the needs of the tunnel designer and geotechnical personnel. There is an iterative learning process involved. As they learn the capabilities and the limitations of the system based on operational results, the system will grow to meet their needs as they see them, rather than on the basis of an apriori established set of goals.

As a minimum, it is anticipated that the system will evolve to collect signatures of known geologic phenomena and hazardous conditions. These will be cause-and-effect phenomena. Some will be predictable on the basis of theory, others will be learned by correlating the observable data with the particular class of feature which produced it.

These signatures, once learned and validated, will be stored in computer memory banks. Similar data from similar conditions would then be compared with the data in the signature bank for rapid identification of the geologic features that produced it.

8.2 EXPECTED DATA

8.2.1 OPERATIONAL DATA

The prime purpose of the system is to assist the tunnel planners, designers, geologists, and other geotechnical personnel with data that is otherwise not available. The initial usable operational data will, in all probability, be relatively crude signatures of significant rock characteristics. For example, a gross structural change will be observed. It will be identified as existing at a specific range in a specified quadrant. This will serve to alert the interpreters to the possibility of a hazardous condition. They will then have to correlate this data with that available from other sources. As a minimum, it may provide a target for an additional drill hole to provide added accurate data for tunnel design.

Realism would dictate that, initially, operational users will place little confidence in the unsubstantiated interpretations based upon the results from this tool alone. It will only be after a large body of experience has validated actual interpretations that confidence will build in the operational data derived by the use of this tool.

The data gathering capability of the tool will far exceed the ability of available personnel to interpret it. There is risk of inundating the user with data. One of its initial weaknesses of the system will be that it will not differentiate between important and unimportant targets and returns. Although there will be a wealth of data, only the massive and gross structures will probably be initially identifiable.

Signatures will exist for faults, joint planes, angular orientations, voids, water-bearing cavities and faults, changes in rock types and strengths, and many other features. These will exist in the radar and acoustic returns. The resistivity probe and some of the simpler features of the acoustic probe will provide data through the bulk characteristics of the rock. These will be much more crude, but initially will probably be of greater operational value. It will only be as data interpretation techniques discussed in the following paragraphs are refined that the full capabilities of the more sophisticated techniques will evolve.

8.2.2 TECHNICAL DATA

The sensing system resulting from this program has been defined in the detailed specifications. It has been defined to the maximum degree possible based upon available data. Measurements and tests which were not part of this program will be needed prior to defining its final configuration. Sufficient laboratory and engineering tests can be conducted to field the prototype. However, there will be a large block of data which can only be obtained by in-situ measurements in the true borehole environment.

A certain percentage of the tests and measurements made with the prototype system should be allocated to collecting technical data. Laboratory and handbook values for such characteristics as attenuation rates, electromagnetic and sonic velocities, and resistivity values are needed to define the technical parameters of the system. However, these are poor substitutes for in-situ measurements. The prototype has been specified on the basis of the best available data. However, this could be in error, in some cases, by an order of magnitude. Before the prototype can grow to its full potential, additional data of this type must be available, and the tool itself will be the mechanism by which it is gathered.

8.3 DATA INTERPRETATION

8.3.1 PROBABLE INTERPRETATIONAL TECHNIQUES

It was known at the start of this program that there was a wealth of material, both in computer programs and interpretational material, which could be directly applicable from the seismic exploration industry. A routine set of programs could be run on the data to improve its interpretability. However, experience on collateral programs indicates that there are many additional programs and algorithms which must yet be developed.

Initially, each new survey will present new problems. They must be attacked individually. Certain interpretable signatures are already evolving. There is the hyperbolic return from points and certain types of line scatterers. Joint planes, and probably faults, are showing up as identifiable signatures. These can be identified and catalogued.

The major weakness of the system will be that the mass of available data will inundate the interpreter. Future interpretational techniques will, in all probability, stress the development of statistical designators. These will be similar to the RQD (Rock Quality Designator) currently used for drill core data. Reliance will be placed upon such features as:

- The statistical spread, or distribution and concentration, of joints around specific angles.
- Depth from which returns are received (Lack of returns can also be significant)
- Spectral content of returns
- Ratios of acoustic to electromagnetic returns
- The use of returns to select additional drill hole locations
- Measurement of the spectral and cepstral phase
- Correlation between returns and available core data to extrapolate trends away from the borehole.

The major task in interpretation will be to selectively reduce the dimensionality of the data into a few meaningful signatures of rock characteristics of interest to the users. This will require a multi-disciplinary approach. It will involve a team of:

- Geotechnical personnel who know the needs of the users and are alert to the geological phenomena which would be of interest.
- Technical personnel who know the equipment, its strengths, and its limitations.
- Processing personnel who know what can and cannot be accomplished on a computer.

Eventually, many team members can be replaced by a single trained man. However, he will need an interdisciplinary background for which there are currently no educational programs. Thus, the interdisciplinary team provides the best compromise. As the team learns to identify and interpret the available data, two classes of interpretation are expected to emerge:

- One class will fall into the category of target signatures. There will be certain patterns of response which will have high correlation with predictable geologic structure. There will be strict formalized rules to testing and identifying these features. When these rules and procedures are formalized, they become signature algorithms which can go into a signature bank. As these evolve, the skill level of the team can gradually be lowered. The ultimate goal would be to reduce the interpretation to a simple bulk processing of data from which would emerge the majority of interpretations in a simple format of value to, and in a form familiar to, the users.
- The second class of data will require the interpretational skills of the team. These will be judgment type of interpretations. The goal of the program should be to move as much of the data from this class to the first class as soon as possible.

8.3.2 SOURCES OF ERROR

The appendices to this report cover the various sources of error, and the means available to reduce them. The question remains, what is the net result in predicting errors or confidence levels in quantitative interpretation?

Actually, the question becomes almost academic when viewed from the pragmatic aspect of the economics and time scales of the user. The initial interpretations will be more qualitative than quantitative. Thus, sources of error should be considered from both standpoints.

- Qualitative errors will be those of interpretation. These have been discussed in previous paragraphs. The sources will be human. As experience is gained and signatures evolve, errors will decrease and the confidence level in the tool will increase.

  There seems to be a natural procedural evolution which will occur. It will start with skepticism where the system results will be accepted only to the degree that they correlate with known or suspected phenomena. As unidentified targets are recognized, these will then be used as targets for drill holes so that their cause may be physically verified. At this point, cost savings can start to accrue by gradually requiring fewer and fewer boreholes for site investigation. Finally, as confidence grows, the results will be accepted and the tool will begin to approach its full capability.

- Quantitative sources of error can be reduced to those resulting from measurement. They will include:

  -- Range errors due to pulse lengths, attenuation of higher frequency components of the signal, and indeterminacies in the velocity of propagation.

  -- Velocity errors due to differing propagation velocities within the medium. Most computations will depend upon bulk velocities, either predicted or measured. These will in general be in error, as it requires a velocity contrast for a reflection to occur. Thus, the bulk velocity will be the average of that of all the medium, not the specific layers.

- Azimuthal errors due to the finite resolution of the system. This will be a function of borehole size.
- Azimuthal errors due to refraction effects at interfaces.

In general, procedures exist to minimize all of these errors. Theoretically, they can be brought down toward the finite limit of uncertainty inherent in the quarter wavelength resolution phenomena. From a practical aspect, the processing costs and developmental costs will limit the reduction achievable. It seems probable that the system will stabilize at some practical level of qualitative and semi-quantitative interpretation. Just where this level will fall will be governed by the practical and economic considerations of the operational environment in which it must survive.

8.4 PROJECTED SYSTEM GROWTH

8.4.1 MODULAR GROWTH

The modular concept and the design for modular growth has already been covered in detail in this report. It will not be repeated. However, for planning purposes the first projected modular improvements should be considered. The growth direction taken beyond that point will depend upon the system and its acceptance by the tunneling industry.

The first needed improvement is expected to be the reinstatement of the downhole thrust device. This will tend to release any restraint on borehole length. Appendix J covers the considerations of using the drill rig as a propulsive device. The principal feature in its favor is its ready availability. However, this is countered by foreseeable difficulties as the hole lengths increase. The specifications for this system are written with this growth in mind.

The next major growth step is anticipated to be a field mobile, possibly real-time computational center. Historically, the management and control of data between the field and the computer has been the weak link in using the computer for advanced data processing. It is anticipated that when this system proves its utility the cost effectivity of incorporating a dedicated computer, probably field mobile, will become more evident.

In general, it is believed the trend in modular growth will be from the system specified toward the configuration of the second baseline system which evolved as a result of this study.

8.4.2 ECONOMIC TRENDS

In order for this system to survive in an economically competitive environment, it must provide either superior information to that achievable by other techniques or it must provide equivalent information at a lower cost, or both.

One of the basic premises in the development of the system has been that it could either eliminate or reduce the need for pilot tunnels. Appendices P and Q address some of the economic considerations involved.

Realistically, it does not seem that this system will replace pilot tunnels in the near future. Too much remains to be proven. However, the economic trends are all in its favor. Pilot tunnels are expensive. There does not seem to be any mechanism by which their future costs can do anything but increase. The same is not true with horizontal boreholes. The main feature which has held the cost of these boreholes high is the lack of demand. There are numerous techniques available to drastically reduce these costs. If the development emphasis and the demands increase, these costs can come down. This has been amply documented in the Federal Highway Administration-sponsored study on "Drilling and Preparation of Reusable, Long-Range Horizontal Boreholes in Rock and in Gouge" conducted by Foster-Miller Associates, Inc. [11].

It would seem that the projectable economic trends are in favor of this sensing system, provided (1) the system proves its value and (2) the art of horizontal drilling is given the developmental support necessary to extend its capability and reduce its costs.

8.5 CORRECTIVE MEASURES

8.5.1 AZIMUTHAL RESOLUTION

Insofar as possible, the system defined in the specification has been selected so that the developmental problems are minimized. The goal was to define a prototype where the technical approach could be limited to resolving the final engineering problems of packaging for form and fit. With the exception of radiating and receiving acoustic and radar transducers to provide azimuthal resolution, this goal has been accomplished. Additional work is needed to insure the achievement of good angular resolution from the confined borehole.

Theory and the limited experiences reported in Appendix L indicate that azimuthal resolution is achievable. However, there is a gap between theory and practice which good engineering dictates should be filled as soon as possible in the follow-on effort. Since there are no in-situ data from which to draw, a program to gather such data is recommended. This program should be carried out for both the acoustic transducers and the radar antennas. The theory and mathematics involved are complex and many assumptions concerning the characteristics of the ground must be made. Thus, it is anticipated that considerable engineering empiricism will be required to obtain satisfactory angular resolution, over the braod frequency bandwidths required.

This program would involve transmitting and receiving within shallow vertical 6-3/4 inch (17 cm) boreholes to validate the proposed approach and to insure that the transducers involved with the prototype will provide satisfactory resolution wihtout undesirable side effects.

8.5.2 PROCESSING ALGORITHMS

The data processing algorithms included in the specification are those which have been used successfully in surface and some subsurface work. However, they have not been adapted to borehole use. Borehole data is needed to refine these algorithms and probably new ones will be needed to account for the peculiarities of the borehole. A certain amount of this work can be expected from collateral programs and theoretical derivations. However, it has been our experience that there is inevitably sufficient difference between programs and enough variation between theory and actual field data that an approach dedicated to this particular problem is needed. It is recommended that the in-situ test site be so selected that the data gathered in engineering design of the transducers can also be used to refine and develop the basic algorithms for the data reduction involved with this system. Of course, this would also entail a program to use and refine this data as it becomes available.

8.6 LABORATORY AND FIELD TESTING

The follow-on program assumed as a result of this effort involved the concept of using the prototype to collect data and provide field testing at the same time it gathers data of operational significance. Thus, the requirement for specific laboratory and field tests should be minimized. This is not to imply that the normal engineering testing involved in prototype fabrication can be bypassed. However, specific tests aimed at proof of performance can be either eliminated or drastically reduced.

Although the use of the prototype for collection of both operational and engineering data is a major plus in the approach we propose, it is deficient in one aspect. In general, the operational environment will govern the selection of test sites. Thus, the evaluation of the system and collection of signature identification data will be on a random basis. In addition, the geology of the operational site may be extremely complex, making interpretation difficult.

A parallel test program should be considered. This would be conducted in areas where known geologic conditions of interest exist. Specific tests and measurements in these areas should be conducted. The sites and tests should be carefully planned and selected so that, insofar as possible, the particular condition of interest is unique. It is desirable to establish the signatures of these features without extraneous signals in the data.

These tests could probably be conducted in vertical boreholes, and possibly from boreholes of opportunity which have already been drilled, to delineate the particular phenomena involved.

8.7 SYSTEM DEVELOPMENT

The value of the modular approach and the projected system performances discussed in the previous section rest upon system growth. Unless a sound system development program is implemented, these projected improvements will be sterile.

A continuing development program is needed for both the hardware and the software involved. It should be geared to a cyclic iterative approach which takes the operational data, experience, and user reactions and requirements into consideration. Properly planned and organized, this program would insure the modular growth of the system to meet the full needs of the tunneling industry.

A major continuing effort in software development is required.

It should follow the same cyclic growth of gradual refinement and improvement as the hardware. There are also major tradeoffs between hardware and software which must be continually made. Processing costs will be one of the major economic factors in the success of the system. There are many computer algorithms that, once they have been properly defined, could be reduced to hardware at a considerable gain in cost effectivity. Conversely, there are many hardware configurations which, by relatively minor modifications, can reflect into major reductions in processing costs by providing data in a form which requires less manipulation. These are all factors which contribute to the need for a well planned, continuing developmental program.

8.8 FUTURE RESEARCH

The logical delineation between needed future research and the recommended program of growth through an orderly iterative process is not clear. We will define needed future research as a foreseeable requirement which will need some form of added external stimulus in order for it to initially enter the development cycle.

8.8.1 SIGNATURE COLLECTION

The recommended measurement program to study and gather signatures of geological phenomena independently from those collected during normal operations falls in the area of needed future research.

Coupled with this signature collection program is the implied need for the necessary effort to evolve a signature library. The library will include methods of interpretation and eventually automatic identification through correlation of pre-defined signature descriptors, from many independent sources.

8.8.2 DISPLAY

A key feature of this program was to evolve a display system which would present the sensing system results. This was defined to include a presentation format and content in a manner meaningful to civil engineers and tunnel designers and planners.

It is now obvious that no such system exists, nor is it likely to exist without both continued research effort and continued operational interaction with the eventual users.

The best approach available involves an interdisciplinary team which interprets the data and decides upon the most meaningful display methodology and format. Although this is a cumbersome approach at present, it seems to be the only way of satisfying this requirement.

There are numerous technical tools available. Many approaches have been considered, most of which are technologically feasible:

- An interactive CRT (cathode ray terminal) seems to hold promise. The user could call up data in any particular format, plan view or section view. Geologic features would be identified and mapped.
- A computer synthesized three-dimensional hologram has been considered. This would enable the planner to view the data from any of a number of angles.
- Hard copy graphic printout of sections or plan views is feasible. This will probably be the first major step in presentation.

Research is needed to determine the best approach. However, its initiation must await the availability of data from the prototype system. It is only after a better understanding of the capabilities and limitations of the system that an effective, user-oriented display can evolve.

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