UCRL 15141

Nuclear Waste Management Program
Siting Criteria

Review of Geotechnical Measurement Techniques for a Nuclear Waste Repository in Bedded Salt

MASTER

Prepared for
University of California
Lawrence Livermore Laboratory
under
Purchase Orders 5487509 and 6755609

December 1979

CONSULTING
ENGINEERS
INTERNATIONAL ENGINEERING COMPANY, INC.
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SUMMARY

SUMMARY

This report presents a description of geotechnical measurement techniques that can provide the data necessary for safe development--i.e., location, design, construction, operation, decommissioning and abandonment--of a radioactive waste repository in bedded salt. Geotechnical data obtained by a diversity of measurement techniques are required during all phases of repository evolution.

The techniques discussed in this report are grouped in the following categories:

- Geologic, Geophysical and Geodetic
- Rock Mechanics
- Hydrologic, Hydrogeologic and Water Quality
- Thermal

The major contribution of the report is the presentation of extensive tables that provide a review of available measurement techniques for each of these categories. The tables give the purpose of the measurements, the applicable repository development stage, a brief description of the techniques, and references in which detailed discussions can be found. Where possible, the techniques are arranged in the order in which they would normally be used. Table 1-1 summarizes the geotechnical activities for each development stage, coordinated with a licensing schedule. The licensing process shown here is suppositional because regulatory procedures have not been clearly defined.

The techniques are also discussed in the text to the extent necessary to describe the measurements and associated instruments, and to evaluate the applicability or limitations of the method. More detailed discussions of thermal phenomena, creep laws and geophysical methods are contained in the appendices; references to detailed explanations of measurement techniques and instrumentation are included throughout the report.

A large number of techniques are listed. Some of them measure the desired properties directly, others must use an indirect approach to calculate the necessary parameter, and in some cases, no truly applicable measuring technique exists. Recommendations are made where research and development could provide improved or new methods to obtain necessary data.

Geologic formations are never completely isotropic or homogeneous; professional judgment is always required to evaluate the validity of measurements and to decide to what degree the data are representative of the general area. Interpretation, weighting and integration of data produced by all the various techniques will normally be required to develop a reliable model.

Two measurement programs are required: exploration and monitoring. The exploratory program would be designed to determine the naturally existing geologic, geometric, thermal, and hydrologic configuration of a repository site, and to measure the physical properties of the geologic materials at the site. The monitoring program would be designed to measure any changes in baseline conditions resulting from construction and operation of the repository in order to anticipate potential leakage or rock instability, and to assess the long-term performance of the repository.

The summary below includes research findings for each geotechnical category.

Geologic, Geophysical and Geodetic Measurement Techniques

Geologic measurement techniques are strongly oriented toward exploration, but do have applications required during the emplacement and decommissioning stages of repository development. Trenching, core drilling and logging, aerial photo interpretation, surface mapping, shaft and tunnel mapping, mineralogic and petrographic analysis, and joint indexing and analysis are used to determine the geometry and geologic framework of the repository site. A considerable amount of interpretation may be required and it is frequently necessary to assume a continuity of geological conditions in order to project data from one area to another.

Geophysical measurement techniques are also mainly exploratory in nature. In most cases, geophysical data are correlated with geologic data in order to increase confidence in the results. Aerial and remote sensing techniques are valuable tools for evaluating regional geologic features as observable from surface expressions. Ground-based seismic, electrical, gravity, and magnetic surveys can be used to delineate geologic structure below the surface. Both regional reconnaissance surveys and more intensive local surveys can be conducted. Both airborne and ground-based methods are capable of collecting valuable data quickly without the need for more costly and time-consuming underground geologic methods.

Geodetic techniques are generally well-established and reliable and are used to establish baseline measurements and to monitor movements during construction, operation, and after decommissioning.

Rock Mechanics Measurement Techniques

Rock mechanics measurement techniques have advanced rapidly over the past three decades. It is now possible to measure underground stresses, stress changes, rock elastic properties, and rock deformations. Laboratory techniques for testing rock cores have also been improved.

Rock stress measurements in boreholes employ open-hole, soft-inclusion or hard-inclusion probes. Overcoring around some of these probes allows calculation of in-situ stresses. Other probes can be installed in boreholes and left for monitoring stress changes over time. In-situ elastic properties can be measured by jacking tests; techniques for measuring rock deformations and tilt are well developed. New instruments are being developed for measuring lateral as well as axial deformation of boreholes.

Research is required to determine the influence of high temperatures upon all rock mechanics instrumentation because many instruments will be used to obtain data both before and after waste emplacement. Instruments that will operate reliably at high temperatures need to be designed, especially for stress-change monitoring and deformation measurements.

Hydrologic, Hydrogeologic and Water Quality Measurement Techniques

Hydrologic, hydrogeologic and water quality measurement techniques are generally standardized. Hydrologic and hydrogeologic techniques can be used to establish the water balance between the repository and the surrounding area. Water quality measurements can be used to establish baseline water properties and to monitor changes in those properties.

Many new techniques for analyzing water quality have been developed in recent years. These include automatic sampling systems, automatic streamflow monitoring systems, and highly sophisticated laboratory analyzers.

At present, no reliable in-situ measurement techniques exist for determining water migration through highly impermeable rocks, especially those in which flow occurs mainly through fractures. Pumping tests, plug tests and most injection tests are not applicable for determining permeabilities or storage coefficients. Research and development are required in the areas of rock fracture evaluation, the effects of stress on permeability, interaction between dissolved minerals and the rock, water sampling in relatively impermeable rocks, temperature effects on fluid flow and rock permeability, and the use of chemical tracers.

Thermal Measurement Techniques

Thermal measurement techniques are not well developed. The capability exists to measure rock temperature and thermal conductivity in boreholes, but is limited to temperatures below 200°F. Als... vailable thermal conductivity probes measure radial conductivity onl... eat capacity can be estimated from some thermal conductivity probe measurement data, but little effort has been made to develop the instrument techniques. No techniques are available to measure the emissivity or heat transfer coefficients of rocks underground. In-situ heater tests in rock chambers have been conducted but only to a limited extent. Techniques reported in these tests do not suggest ways to monitor the large-scale thermal behavior of a waste repository. No borehole heater techniques for use in mines have been reported.

Laboratory tests exist for thermal conductivity, heat capacity, emissivity, and heat transfer coefficients. Except for thermal conductivity tests, these techniques have not been developed specifically for rocks. New testing techniques need to be developed. In addition, research and development for determining rock thermal properties are needed for salt, shales, and other associated rocks.

There is a strong need for research and development efforts in the thermal area. The effects of heat upon rock properties, the development of standardized thermal testing procedures, the development of in-situ thermal tests, and the creation of new measuring instruments all need to be addressed.

CHAPTER 1
INTRODUCTION

The collection and organization of geotechnical information is a fundamental requirement for all aspects of the installation and operation of a nuclear waste repository in bedded salt. In particular, site selection, design preparation, and repository effectiveness assessment cannot be executed without reliable, accurate geotechnical information. This information can be obtained only by observations and measurements taken at a particular site and upon the geologic materials collected from that site. This report presents a state-of-the-art review of available techniques for making these observations and measurements.

Geotechnical information can be classified into two broad categories: baseline site data and monitored site data. The former are generated during exploration and would be used mainly for the selection, evaluation, design, and development of a repository site. The latter are generated during and after repository operation and would be used mainly to assess repository effectiveness.

Baseline site data are used for the construction of a complete three-dimensional model of the site geologic conditions. This model would include the location and orientation of all geologic strata, an identification of all major structural features (faults, joint pattern and spacing, and folding), chemically altered zones, and other geologic features. Also included would be supplementary information describing rock and salt properties, characteristics that would influence repository geohydrology--e.g., rock porosities and permeabilities, aquifer locations and characteristics, and fracture information. Once this model has been sufficiently developed, detailed decisions about where and how to emplace waste can be made.

Monitored site data are used for several purposes. First, the data provide actual operating knowledge about the behavior of the rock and groundwater system at depth. This information can be used as feedback into the original repository design so that appropriate adjustments can be made. Second, the collection and review of site data can act as a warning device against possible rock failures, waste leakages, rock temperature increases and other possible adverse effects. As time passes and more and more information about the repository is collected, a general understanding of normal behavior is developed so that abnormal behavior can be recognized quickly. Finally, monitored data provide a realistic data base to assess a repository's capabilities for (1) long-term containment and (2) unobstructed waste retrieval. In particular, the interaction between rock behavior and ground-water flow can be more fully evaluated after a repository becomes operational.

1.1 PURPOSE AND SCOPE

The purpose of this report is two-fold. First, it is to present in tabular form available geotechnical measurement techniques that can be used to collect data for siting and monitoring nuclear waste repositories in bedded salt. Second, it is to assess each technique with regard to its reliability, accuracy, measurement limitations, and research and development needs.

Geotechnical measurements include visual observations and instrument measurements--both in situ and in the laboratory. In this report, four categories of geotechnical measurements are treated:

- Geologic, Geophysical and Geodetic
- Rock Mechanics
- Hydrological, Hydrogeologic and Water Quality
- Thermal

Geotechnical properties of environmental baseline parameters are incorporated within the four categories listed on the previous page. Geochemical studies were not included in the scope of work.

Tables concluding Chapters 2, 3, 4 and 5 list the parameters most useful for evaluating a repository. With each parameter are listed measurement techniques, the purpose for which the technique is used, the repository development stage in which it can best be applied, and pertinent remarks pertaining to the operating principles of the measurement instrument or to the usefulness of the information obtained.

The text presents introductory discussions of the parameters and measurement techniques listed in the tables. These discussions are designed to explain why and how data are obtained. Also included, where applicable, are evaluations of the reliability and accuracy of the instruments. Attention is drawn to areas where instrument research and development are needed.

Supplementing the text are appendices that provide detailed technical background for three of the measurement technique categories. Appendix A more fully explains present-day geophysical instrumentation and survey techniques. Appendix B presents a basic discussion of rock stress-deformation characteristics and a discussion of rock creep phenomena and its associated parameters. Appendix C introduces thermal phenomena and its associated parameters.

1.2 UNCERTAINTIES IN GEOTECHNICAL MEASUREMENTS AND DATA ACQUISITION

Geotechnical measurements are subject both to observational errors and to interpretational errors. Observational errors depend upon the accuracy and reliability of the instrument or the observer. Interpretational errors always depend upon the experience, knowledge and judgment of the interpreter. There are two categories of data to consider: exploration data and monitored data.

In many cases, observational errors can be identified fairly easily, particularly if they are large errors. For example, if an instrument is not calibrated, or an operator makes faulty readings, improbable conclusions are drawn. At the same time, small errors occur and are more difficult to identify. For this reason, each measurement technique's limitations should be fully known and accounted for during data interpretation. Multiple readings and comparisons with alternative instruments are often used to check for small errors.

Interpretational errors are directly related to the amount of data acquired. In most instances, interpretations must be made with insufficient data, so that no matter how accurate are the data, errors in human judgment can produce false results. During exploration, errors in judgment are expected; therefore, strong reliance is always placed upon cross-checking with data from different sources. As more and more information is collected over a period of time, the confidence level in the data increases, and refined interpretations can be made.

The acquisition of monitored data is also subject to errors of observation and interpretation. If the monitored data are used for warning and control functions in a repository, then data accuracy and instrument reliability are of paramount importance. If a danger develops--such as overheating in pillars--it must be detected rapidly and unfailingly. If monitored data are to be used for design feedback, again data accuracy and instrument reliability are important. Otherwise, design errors may occur which could lead to inadequate conditions for waste isolation. In addition, if the instrument fails, there is usually time to install a new one. If the monitored data are to be used for long-term assessment of repository effectiveness, then the time element becomes of paramount importance. Observation techniques must be reliable over long time intervals, or must be such that they can be repeatedly reintroduced with consistent accuracy.

1.3 DEVELOPMENT SCHEDULE

This report answers two basic questions: What should be measured? Can it be measured? The answers necessarily relate to the development stages of a repository: each stage has its own requirements for information. For example, during early geologic reconnaissance, only general site geology and representative rock properties are required. From major geologic structural features and rock strength data, a schematic picture can be developed for qualifying the site for further exploration or for rejecting it as being unsuitable. If the site appears to be acceptable, then more information is needed. To determine if the site is feasible, detailed information about geologic conditions at specific locations underground must be obtained. Extensive drilling, sampling, and geophysical work are required to outline more completely the geologic configuration of the site, and to define rock properties. One of the basic problems of site exploration will be integrating the drilling program with the requirements for adequately sealing storage areas. This may include limiting drilling in order to reduce the risk of failures in borehole seals. After a specific site is selected, even more information is needed. At this stage, the focus of the exploration effort changes. Information about the rock at specific underground locations is required. Shafts and rooms must be located, access tunnel routes laid out, possible ground-water flow channels identified, aquifers located and tested, and a host of other tasks performed. All exploratory activities must be carefully planned to minimize disturbance of rock in the vicinity of the selected repository site.

Presented in Table 1-1 is a preliminary program designed to indicate the type of geotechnical measurements needed during each stage of repository development. For each stage, techniques that will receive the most use are shown for the four categories adopted in this report: Geological, Rock Mechanics, Hydrologic, and Thermal. It should be emphasized, however, that all of these techniques can be used at any stage of development, provided there exists suitable access as required by the technique.

Also shown in Table 1-1 is the connection between the development stages and the regulatory process as now used in the nuclear industry. In broad terms, any underground project can be represented by a series of activities separated by a series of decisions. As each activity is completed, a decision has to be made as to how, when and if the next stage shall be initiated. During all work, these decisions are made continuously; however, certain ones always play a major role. For current nuclear regulatory procedures, these major decisions are represented by license and permit approvals. In Table 1-1, the timing of these approvals is shown in relationship to the development stages.

The stages adopted for this report are based upon the normal process of project development used in engineering underground structures and mines:

A. Site Selection

1. Areal Reconnaissance - Broad-based review of potential site geology, hydrology, rock mechanics and rock thermal properties.

2. Detailed Investigation - Full-scale exploration into the geotechnical suitability of the site as a waste repository.

3. Detailed Design - Full-scale design of all underground facilities including shafts, tunnels, rooms and support facilities.

B. Construction

Full-scale construction of all facilities needed for the initiation of emplacement--including shaft, tunnel and room excavation, and the installation of equipment.

C. Emplacement

All forms of waste emplaced over the life of the repository.

D. Decommissioning

1. Sealing - Rooms, tunnels and shafts sealed and the repository vacated.

2. Monitoring - Measurements in the site vicinity made to insure continued integrity of the repository.

3. Abandonment - Repository sealed and abandoned for a long period of time; monitoring ceases.

During Stages A.1 through A.3, most information collected will define naturally existing conditions and will be used mainly for describing the repository. Descriptions will include the geologic structure of the site, the hydrologic behavior of local and regional ground-water flow, the thermal heat flows at the site, in-situ and laboratory rock properties, and any other factors that could affect repository operation, long-term containment, and environmental impact. During Stage B, additional geotechnical information will be obtained, and pre-emplacement monitoring instruments will be installed and tested. During Stage C, most information generated will be monitored data from the storage operations. During Stages D.1 and D.2, monitored data will predominate, although in-situ and laboratory testing will be performed for designing seals. For a certain period after sealing, monitored data will continue to be collected. During Stage D.3, the repository is assumed to be totally abandoned.

1.4 INSTRUMENTATION STRATEGY AND THE REGULATORY PROCESS

It is difficult to specify in regulations which geotechnical measurement techniques should be used, or when, why, where and how they should be used. The basic need is for quality information and not necessarily the specialized information from a single instrument or data analysis technique. As experience in the mining and petroleum fields shows, first a decision must be made as to what type of information is required, and then the decision is made as to how to obtain it. For the case of a waste repository, the information required will be related to the regulatory requirements of that repository. These requirements will be related to the stability of the underground openings and the long-term waste containing ability of storage areas. Requirements for specific information can be included in the regulation, but flexibility should be given to the repository operator as to how to obtain it.

Two measurement phases need to be detailed, however, because they are critically important in the regulatory cycle. These are (1) geotechnical exploration--to determine the characteristics of site--and (2) geotechnical monitoring--to detect and identify possible adverse conditions (especially conditions favoring waste leakage) within a repository.

A. Comments on Exploration Strategy

The basic problem of exploration is to define the geologic nature of a site, including the types and physical properties of rock present, the geometric configuration of those rocks, the location and orientation of structural features such as faults, joints, folds, and fractured areas, and the groundwater system. Exploration must be sufficiently detailed to provide adequate information to assess the rock stability and containment capabilities of a site. This information may be obtained from large- or small-scale investigations--i.e., from feasibility exploration of an entire repository site or from analysis of a particular storage panel underground.

It must be emphasized that exploration is a process of search and identification. It consists of a series of cyclical programs of establishing target areas, exploring those targets with geotechnical measurement techniques, analyzing and reporting the results; and then establishing new target areas. The cycle is repeated again and again with different levels of effort until an orebody, oil pool, gas reservoir, or repository site is found.

As exploration progresses, some target areas will be rejected and others accepted. Exploration effort will intensify and become concentrated upon a few favorable sites. The emphasis will change from surface to subsurface exploration methods. Core drilling and sampling and borehole geophysical testing will increase. As more data are collected, the level of confidence in the information describing the site geology and groundwater conditions will rise. Next, an exploration shaft will be sunk to targeted rock strata and preliminary in-situ tests performed. Eventually, the confidence of the operator will increase to a point where he feels that one or more sites are feasible and the information describing those sites is adequate. He will then apply for approval. At this point, the regulator will have to review the exploration and decide for or against approval.

In all underground projects there is always an element of risk involved in assuming that the maps, diagrams, data compilations and written reports generated from exploration accurately represent underground conditions and can provide the basis for predicting future repository behavior. For a facility as sensitive as a waste repository, there will be a strong tendency toward obtaining as much information as possible. Experience has shown that the most reliable and accurate information about rock strata underground comes from core drilling coupled with sampling, geophysical logging and borehole testing--followed eventually by shaft sinking, tunneling, and in-situ testing. However, extensive core drilling may adversely affect waste containment because every borehole is a potential leakage path. Since there are strong doubts about the long-term effectiveness of presently used borehole seals, it is not reasonable to perforate a storage location with drill holes. Thus, the need for drilling (to describe adequately waste storage target areas) is matched against the requirement for preserving the containment capabilities of the targeted rock. This tradeoff creates a difficult challenge for the field of exploration strategy.

In order to emphasize the exploration strategy problem, two areas of special interest are identified. First, in order to evaluate the containment capabilities of a particular repository site, accurate permeability data must be obtained and incorporated into ground-water flow and diffusion modeling. Rock permeabilities include pore permeability, fracture permeability and, possibly, permeability resulting from joints and faults. The task of identifying these accurately without extensive drilling is formidable.

Second, in order to evaluate the effects of canister heat upon rock stab ty, upon the operating environment, and upon retrieval and waste containme.., accurate thermal properties must be determined and incorporated into the heat flow modeling. Therefore, rock thermal property data should be obtained through laboratory sample testing and, possibly, in-situ borehole heater tests. This requirement in turn creates a need for exploration drilling. Thus, in addition to the basic need for collecting purely descriptive information, the exploration strategy must consider sampling and testing together with modeling.

Drilling restrictions can be managed several ways. One approach is to conduct limited surface drilling to outline broad targets, and then convert to highly controlled drilling from underground stations. Exploration shafts and tunnels would be required during the exploration program. A second approach, perhaps in conjunction with the first is to use geostatistical techniques for planning the drilling and analyzing the resulting data. Geostatistical analysis techniques have not as yet been developed for the special conditions unique to a repository.

B. Comments on Monitoring Strategy

Any repository monitoring program must be designed to detect and identify possible adverse conditions in a repository that could affect the health and safety of workers, the structural stability of storage rooms (and, thus, canister placement and retrieval operations), the structural stability of access tunnel and shafts (and, thus, underground transportation and ventilation), and the containment capabilities of storage areas. The basic problem of monitoring is first, to identify possible adverse conditions; second, to select instruments to detect those conditions; third, to develop an instrumentation plan to install the instruments; fourth, to develop a data acquisition plan, and finally, to install the instruments.

The identification of possible adverse conditions in a repository requires a review of all previous exploration findings, possible additional exploration work, in-situ rock mechanics tests, in-situ permeability tests, in-situ heater tests, and laboratory tests. All of this work will be aimed at creating a data base for subsequent monitoring. The monitoring program also requires instrument testing, calibration and modification.

A full-scale geotechnical monitoring program must address a number of important factors, among which are

- Canister/waste interaction
- Canister/rock interaction
- Waste/rock interaction
- Storage room stability, including structural condition of the floor, roof and pillars
- Access route stability, including ventilation tunnels, men and material tunnels, waste haulage tunnels, inclines, shafts, raises and other openings
- Rock fracturing behavior both in storage room areas and in the surrounding strata

- Heat flow rates and temperatures in the rock adjacent to storage rooms
- Heat flow rates in repository rocks on a regional basis
- Ground-water flow, temperatures, and quality in aquifers associated with the repository
- Rock permeability changes within rock strata adjacent to storage areas
- Borehole, shaft and tunnel seals, including permeability of new and old seals.

The monitoring program will include visual observation, periodic in-situ testing, periodic sample testing, and continuous data read-outs from in-situ instruments.

The development of a monitoring strategy for any repository will depend upon the geotechnical conditions found at the site, the mine plans for the repository, and the design plan for canister storage and retrieval. In general, instrumentation, measurement techniques, and data analysis methods exist for rock stability monitoring and the behavior of ground water in aquifers. There are two areas of especial concern in which measurement techniques have not been adequately developed and in which experience is minimal:

- The effects of a strong, localized heat source upon rock behavior underground--including possible temperature increases, reductions in rock stability, increased creep rates, and rock fracturing processes

- The ground-water flow behavior and the hydrologic properties of rocks of very low permeability--including fracture permeability.

Regulations should require a geotechnical monitoring plan during each stage of repository development. These plans should include a description of monitoring strategy as well as a description of instrumentation use and data analysis procedures. The regulator should have the right to approve or disapprove each plan, and to make inspections once the plan is instituted.

For most cases, monitoring plans can be prepared with presently available measurement techniques. For example, room stability can be monitored with rock-deformation, stress, and stress-change measuring instruments. However, no definitive monitoring program can yet be developed for the two areas mentioned above (rock heat flow and low-permeability groundwater flow) where research and development efforts are most strongly needed.

1.5 AUTHORIZATION

The current work was conducted pursuant to Purchase Order 5487509, dated 9 April 1979, and Purchase Order 6755608, dated 5 September 1979, issued by the University of California, Lawrence Livermore Laboratory.

TABLE 1-I

Sheet 1 of 2

REPOSITORY DEVELOPMENT STAGES AND THE APPLICABILITY OF GEOTECHNICAL MEASUREMENT TECHNIQUES

Development Stage	Licensing Milestone	Geologic, Geophysical and Geodetic (Refer to Ch. 2 and Table 2-1)	Rock Mechanics (Refer to Ch. 3 and Table 3-1)	Hydrologic, Hydrogeologic and Water Quality (Refer to Ch. 4 and Table 4-1 to 4-5)	Thermal (Refer to Ch. 5 and Table 5-1)
I. SITE SELECTION AND DESIGN Reconnaissance Prefeasibility Report		Employ aerial and satellite remote sensing techniques; conduct geophysical reconnaissance, rock sampling, geologic review and limited mapping, seismic reconnaissance, limited core drilling.	Perform limited testing for rock properties.	Conduct preliminary streamflow measurements, preliminary rainfall analysis; review groundwater data.	Conduct limited laboratory testing for thermal properties.
	PRELIMINARY CONSTRUCTION AUTHORIZATION				
Detailed Investigation Preliminary Design Feasibility Report		Perform detailed geologic mapping, core drilling, seismic refraction and reflection surveys, borehole geophysical logging, extensive core sampling, earthquake studies, microseismic studies.	Extensively test cores for strength, elastic properties, and creep.	Conduct full water-balance study, pumping tests, streamflow measurements, permeability tests, laboratory studies of porosity and permeability; establish baseline water quality data.	Measure borehole conductivity temperature, and thermal capacity; test geochemical properties in the laboratory; establish geothermal gradients.
	CONSTRUCTION AUTHORIZATION				
Detailed Design		Exploration shafts and tunnels; underground core drilling; continue surface mapping; map shafts and tunnels.	Continue core testing; make in-situ jacking tests; overcore for in-situ stress measurements; install deformation gages	Conduct in-situ permeability tests; install groundwater piezometers; install test wells; make aquifer pumping tests; make mine drainage observations.	Perform in-situ thermal tests in boreholes and underground rooms, and laboratory tests; preliminarily determine emissivity and heat transfer coefficients.

TABLE 1-1

REPOSITORY DEVELOPMENT STAGES AND THE APPLICABILITY OF GEOTECHNICAL MEASUREMENT TECHNIQUES

Development Stage	Licensing Milestone	Geologic, Geophysical and Geodetic (Refer to Ch. 2 and Table 2-1)	Rock Mechanics (Refer to Ch. 3 and Table 3-1)	Hydrologic, Hydrogeologic and Water Quality (Refer to Ch. 4 and Table 4-1 to 4-5)	Thermal (Refer to Ch. 5 and Table 5-1)
B. CONSTRUCTION		Underground core drilling; perform in-situ geophysical tests; tunnel geologic logging; install micro-seismic monitoring system; monitor mine seismic events.	Continue in-situ tests, overcoring and jacking tests; install long-term deformation and tilt gages; install stress-change devices in boreholes.	Monitor all test wells; continue in-situ permeability tests; perform special in-situ tests; install storage-room permeability monitoring devices.	Install long-term temperature probes; determine in-situ emissivity, diffusivity and heat transfer coefficients; install heat rate monitoring instruments; perform new instrument R&D; perform laboratory tests on rock samples; and perform ventilation tests.
	EMPLACEMENT AUTHORIZATION				
C. EMPLACEMENT		Map geology of newly excavated areas; continue rock sampling.	Monitor rock deformation, rock stress, and changes in rock properties.	Monitor surface-water balance, ground-water flow, mine-water flow, water quality over and near repository; continue in-situ permeability tests.	Install thermal probes (heat-flow and temperature) in storage room areas; monitor rock temperatures and heatflows in storage areas, access tunnel areas, and throughout repository.
	DECOMMISSIONING AUTHORIZATION				
D. DECOMMISSIONING					
Sealing		Map geology of seal and plug areas; rock sampling; conduct limited core drilling.	Perform in-situ tests for seal design; monitor deformations in seals and plugs.	Monitor surface-water and ground-water quality and flow; monitor mine-water flow; test borehole, shaft and tunnel plugs.	Monitor rock temperatures and heatflow.
Monitoring		Explore to assess ground conditions; geophysical and geologic methods same as for Stage A.	Remotely monitor rock stress and deformation.	Perform streamflow analysis; install ground-water wells: make pumping tests, plug tests, permeability tests, etc., as site conditions warrant.	Monitor rock temperatures and heat flow; measure conductivity and diffusivity and other properties as site conditions warrant.
Abandonment					

CHAPTER 2

GEOLOGIC, GEOPHYSICAL, AND

GEODETIC MEASUREMENT TECHNIQUES

2.1 INTRODUCTION

The measurement techniques discussed in this chapter are grouped (as nearly as possible) in the order in which they would be applied in the location and evaluation of a repository site. The approach is taken from a general regional appraisal to detailed investigation of a specific site. Included are geologic and geophysical measuring techniques for evaluating from a distance geologic structure, stratigraphy and lithology through the application of remote sensing and airborne geophysics, those techniques that are performed on the earth's surface or in shallow excavations, and those that require drilling of exploratory holes.

Much of the information that is derived from remote or surface measurements should be applied with caution to the assessment of probable geological conditions at depth because geologic structure is rarely constant. These methods provide a general understanding of the area, however, and allow identification of questions requiring further clarification.

2.2 AIRBORNE TECHNIQUES

A. Remote Sensing

Remote sensing includes various methods of collecting information about the earth without being in direct physical contact with it. It normally is performed from aircraft and satellites and is restricted to methods that use electromagnetic energy to detect and measure earth properties. Remote sensing does not include measurement of force fields such as electrical, magnetic, and gravity forces. These measurements may be made from aircraft, but they are discussed in the following section, Airborne Geophysical Methods.

Remote sensing techniques are used during the initial evaluation of a prospective area or site. They give an understanding of the gross physical characteristics of an area and allow identification of features requiring detailed direct investigation. Considerable experience in remote sensing interpretation and confirmation of hypotheses in the field are required for reliable results.

Three bands of the electromagnetic spectrum are utilized in remote sensing: (1) the photographic band, which includes the visible spectrum and a small part of the ultra-violet and infrared bands, (2) the thermal infrared band, and (3) the radar band.

1. Photographic Band - The photographic band is the original form of aerial photography, and photographs may be made at wavelengths ranging from ultraviolet into the photographic portion of the infrared region. Various combinations of films and filters can be used with the different spectral bands to obtain the best results under various terrain and weather conditions. Multispectral systems, employing multiple cameras or lenses, are also used to acquire special-purpose photographs. Sabins (1978) discusses the use of various photographic combinations.

Images in the photographic band are acquired with conventional cameras or with optical-mechanical scanning devices. The following types of photography within the photographic band are used in remote sensing:

- Conventional black-and-white
- Infrared black-and-white
- Color
- Infrared-color
- Multispectral
- Ultraviolet

Conventional black-and-white photography is the most widely used type because stereo coverage of most of the United States is available at modest prices from government agencies. Experienced interpreters can readily distinguish geologic features on black-and-white photographs.

Infrared black-and-white photography has the following advantages over conventional black-and-white:

- Improved haze penetration produces a higher contrast ratio and higher spatial resolution.

- Maximum reflectance from vegetation occurs in the photographic IR region and produces bright tones.

- Infrared absorption produces clear land-water boundaries.

Color photographs are generally superior to black-and-white for geological interpretation because the human eye can discriminate many more shades of color than it can tones of gray. Infrared color photography combines the properties of infrared black-and-white with the advantages of color.

Multispectral photography can be used to enhance specific features by obtaining various color combinations. However, multispectral photography is much more expensive, and it has no significant advantage over normal color. Multispectral photographs lack the ground resolution of conventional photographs.

Ultraviolet photography is not widely used in remote sensing because atmospheric scattering produces photographs of poor contrast and low resolution.

The various types of photography can be employed using the three imagery acquisition techniques discussed below.

- <u>Conventional Aerial Photography</u> - Aerial photographs can be used to delineate formation outcrops and structural features, and data derived from photo interpretation can be correlated with information obtained from surface and subsurface investigations to provide a complete geological interpretation of the selected area. Stereoscopic viewing of aerial photographs provides a comprehensive picture, and may reveal features that are not evident from the ground (Miller, 1961; Ray, 1960).

  Numerous photogrammetric instruments are available to obtain quantitative information from aerial photography. Photogrammetric measurements can be used to determine the strike direction and dip magnitude of exposed strata, to calculate the thickness of geologic sections, to determine the offset of faults, and to obtain topographic information. It is also possible to relatively quantify such features as drainage density and fracture density, which can be related to permeability and ground-water recharge.

- Low Sun-Angle Photography - Low sun-angle photography (Slemmons, 1969; Cluff and Slemmons, 1971) enhances topographic differences to give optimum delineation of fault scarps. It is useful primarily to locate faults and lineaments on a regional basis. Low sun-angle photographs show subtle differences in relief and, therefore, are more useful in areas of low relief than in areas of high relief where shadows obscure much of the area (Sabins, 1978).

- Satellite Imagery - Various forms of satellite imagery are used to define surface geology, generally on a regional basis, because the image scale is much smaller than the scale of conventional aerial photographs. Gross features that might be overlooked on the larger scale aerial photographs are sometimes easily discerned on small-scale statellite imagery. Lineaments and geomorphological anomalies of the features that may be observed on satellite imagery are two of the most significant. Such features can be correlated with trends shown on geomagnetic maps and with features determined from surface investigations. Multispectral images may sometimes be used advantageously to display pertinent data (Anuta, 1977; Hughes Aircraft Co., 1972).

2. Thermal Infrared Band - Thermal infrared radiation is absorbed by the glass lenses of conventional cameras and cannot be detected by photographic films. Special detectors and scanners are used to record images in the thermal IR spectral region.

Thermal infrared (IR) imagery records heat flow patterns that are altered by such geologic features as salt domes and faults. Thermal IR can be used to obtain geologic and structural information, to map surface and near-surface moisture, and to monitor environmental conditions (Vincent, 1975; LeSchack and Del Grande, 1976).

Thermal models and empirical correlations with ground features are used to understand the significance of temperature signatures obtained by thermal infrared imagery, and the signatures can be correlated with rock types (Sabins, 1978).

3. Radar Band - Radar is a form of active remote sensing which provides its own source of electromagnetic energy. Side-looking radar (SLAR) is a radar system that acquires imagery from radar pulses directed away from the source at a low angle.

SLAR is the optimum remote sensing system for mapping terrain and geologic structure in forested areas where flying conditions are poor. The low illumination angle of SLAR enhances lineaments. This enhancement is caused by the suppression of distracting detail, reduction of resolution, and radar shadowing of the SLAR system (Sabins, 1978). SLAR imagery provides gross lithologic and structural subdivisions on a regional scale (Viksne, 1969). Two types of SLAR are being used: real aperture and synthetic aperture radar. The two types differ in the method for achieving resolution in the azimuthal direction. The two systems are described by Sabins (1978).

B. Airborne Geophysical Methods

The distinction between remote sensing and airborne geophysical measurements is somewhat arbitrary. Logically categorized as remote sensing methods, aeromagnetic and aerial gamma-ray spectroscopy surveys are usually listed among the geophysical methods since both types of survey are also conducted on the ground.

In comparison, gravity measurements, usually taken on the ground, have also been made by airborne instruments, although with diminished accuracy. Some of the electromagnetic methods are used in aerial surveys for mineral exploration.

1. Gamma-Ray Radiometry and Spectroscopy - Airborne gamma-ray instrumentation was initially used to explore for the radioactive elements uranium and thorium. The technique was later extended for use in geologic mapping (Løvborg et al., 1972) and in monitoring natural radioactivity at reactor sites (Bates, 1964; MacKallor, 1965).

Geiger counters originally used for this purpose proved unsatisfactory, and they were replaced by scintillation counters using thallium-activated sodium-iodide crystals. Multichannel spectrum analyzers are used to determine pulse heights and peak positions (Darnley, 1970). More recently, (Duval et al., 1977), it has been found that large-volume plastic detectors can be used effectively to determine apparent concentration of radioactive potassium, uranium, and thorium (Reeves, 1975). Other new developments in instrumentation have been reported by Chiu and Collins (1978).

Airborne gamma-ray measurements must be carefully calibrated. Corrections have to be applied for cosmic radiation, altitude, aircraft contamination, and Compton scattering in the detectors (Grasty, 1975). Various mathematical techniques are then used to derive geologic information from the measurements (Duval, 1977; Collins, 1978).

2. Magnetics - Magnetic surveys measure total magnetic field intensity at designated locations (Dobrin, 1960; Telford et al., 1976). Measurements of field components do not greatly increase the value of interpretation.

Survey techniques considered here are

- Airborne, conventional surveys, sensitivity 1 to 0.1 nT (nanoTeslas*)

* The Tesla is the Système International (SI) unit of magnetic flux density (Webers/meter^2). One nanoTesla equals one gamma.

- Airborne, high-sensitivity surveys, including gradiometer surveys, sensitivity 0.01 to 0.0001 nT

- Ground surveys, sensitivity 10 to 1 nT.

One factor that has to be taken into account in magnetic surveys is the time-varying nature of the earth's magnetic field. Time variations of the field can be grouped into secular variation, daily variation, pulsations, micropulsations, and magnetic storm activity. During magnetic storms the field variations are so large and rapid that no magnetic surveys should be conducted. Secular variation is not a problem in magnetic surveys; however, for comparison of surveys from year to year, this variation must be considered. Presently available are models such as the International Geomagnetic Reference Field (IGRF) that represent the smooth field of the earth and its secular variation.

Daily and other short-term fluctuations of the field must be considered in acquiring and processing magnetic data. Errors arising from such variations can be eliminated by comparison with base station readings, by survey line arrangements and statistical procedures, or by measuring gradients which, over short distances, are free from diurnal variations.

The anomalous magnetic field plotted as a result of magnetic surveys is dependent on the magnetic susceptibility and remanence of rocks in the area surveyed (Nagata, 1961). For conventional surveys, measurable effects depend entirely on the distribution of ferromagnetic minerals in the earth's crust. Most sedimentary rocks have negligible magnetic susceptibility and are transparent as far as magnetic measurements are concerned.

The magnetic map and profiles resulting from a survey are, therefore, representative of the configuration of basement rocks and other igneous and metamorphic rocks in an area. Magnetic measurements can provide valuable information on the tectonic framework of an area, such as a salt basin considered for repository purposes. Magnetic maps are also an excellent indicator of lineaments which can be compared with other information relating to faults and fractures.

Rock salt is a paramagnetic material with a slightly negative susceptibility. This effect is strong enough to be potentially detectable with modern high-sensitivity magnetometers. A high-sensitivity survey, therefore, may give direct indications of salt configuration.

Airborne surveys are a fast and relatively inexpensive method of covering large areas. They also have the advantage of attenuating near-surface effects which appear as noise in ground magnetic data. Today, ground magnetic surveys are used primarily to investigate locations of possible faults, where displacement and fracturing may produce large local magnetic excursions which would be attenuated in aerial surveys.

Total intensity of the earth's magnetic field, the parameter measured in magnetic surveys, is of no direct significance with respect to bedded salt repositories or their geologic conditions. Instead, magnetic anomaly maps (or profiles), related to the magnetic susceptibility and remanence of rocks, have to be interpreted in order to derive meaningful geologic information. Magnetic maps can give information on rock types (primarily of the basement), on depth to magnetic rocks, and on lineaments and other structural features.

Depth determinations can be considered accurate only to $\pm$ 10 percent--even if the magnetic measurements are accurately made--because of assumptions used in calculating depths from magnetic anomalies. However, a high-sensitivity survey permits a greater number of depth determinations by using many smaller anomalies. In any survey, a number of depth determinations will be inconsistent with other measurements and will have to be rejected because they do not match the assumptions used.

Lineaments and outlines of lithologic units can often be located to within 10 to 20 percent of the depth of magnetic rocks. In general, magnetic maps provide a good picture of basement depth and configuration, and of regional trends and lineament directions. They are of great value in arriving at an overall evaluation of the tectonics of a salt basin.

2.3 GROUND-BASED MEASUREMENTS

A. Geodetic Measurements

Geodetic measurements taken before the emplacement of nuclear wastes will form a baseline reference for monitoring subsequent crustal displacements and deformations. These measurements will be grouped into three subcategories: Survey-related methods for geometric controls, inclinometer-type techniques for the measurement of ground deformations; and pore-pressure measurements, also for the measurement of ground deformations. (After Sharma and Raphael, Measurements Committee, USCOLD, 1979. See Table 2-1, this report, for details.)

- Survey-related methods--such as precise leveling and triangulation, traversing, and photogrammetry, in decreasing order of accuracy (see Gould and Dunnicliff, 1971, for a thorough discussion of accuracy requirements for geotechnical measurements)--provide the horizontal and vertical control data for the site. These data are needed to provide a network of control points to detect crustal movements, and to provide points of reference for the deformation measurements.

- Techniques using inclinometers, slope indicators, tiltmeters, and extensometers provide deformation data by micromonitoring the relative crustal movements near structural features, such as surface faulting and ground cracking. (See Schmidt and Dunnicliff, 1974; and Cording et al., 1975, for state-of-the-art geotechnical instrumentation and techniques.) Micromovements of the underlying strata can adversely affect man-made facilities, and therefore deserve careful scrutiny.

- Piezometers measuring pore-pressure changes provide further information on crustal deformation. Changes in pressure head resulting from ground-water fluctuations (Hvorslev, 1951; Terzaghi and Peck, 1967) could be caused by seasonal and climatic factors

(Sokol, 1966), by human activities (Casagrande, 1949), or by faulting (Zones, 1957). Changes in pore pressure alter the loading and stress regime in the ground, and are important precursors of land subsidence and mass sliding (Carrillo, 1948; Terzaghi, 1962; Lambe, 1972).

B. Ground-Based Geologic Methods

1. Geologic Mapping - Geologic mapping of the surface identifies rock outcrops and surface features to provide information for selecting a suitable repository site. Innumerable geologic mapping methods are available, but most of these are variations of four principal types (Lahee, 1941):

- Compass and clinometer
- Hand-level
- Barometer or altimeter
- Plane table and alidade or other surveying instrument.

Of these four methods, the least precise is the hand-level, used chiefly for rough reconnaissance work. The compass and clinometer method is more precise than the hand-level method, but should not be used in regions underlain by stratified rocks dipping at less than 5 degrees.

The barometer method is more precise than the two preceding methods, but is less precise than the plane-table method. Some advantages of the barometer method over the plane-table method are that

- Only one person is required, whereas the plane table method requires two or more

- The method is less time consuming

- The equipment is lighter and more portable

- The method is less dependent on visibility between points.

Some disadvantages of the barometer method are that

- It requires experienced personnel and reliable aneroid barometers

- Correlation of outcropping strata is more difficult because traverses are commonly set up on straight lines in definite directions or on existing roads

- Barometric readings require constant attention to temperature and need corrections before the map can be made.

2. Joint Mapping, Fracture Analysis, and Lineament Studies - Joint mapping, fracture analysis, and lineament studies will provide information related to the three-dimensional distribution of fractures, joints, and other discontinuities. This information will aid in determining rock permeability, ground-water movement, and stability of the repository site. The information can be acquired by standard mapping methods, and can be analyzed statistically. Such data are most easily evaluated if graphically presented by stereographic projection (Hoek and Bray, 1974).

Information acquired from the mapping of joints on surface outcrops, excavated slopes, and exploration trench walls is essential in assessing the rock quality even though the information cannot be used quantitatively.

3. Trenching - Trenches and test pits are used to confirm and expand data that are observed on the ground surface. Their use permits observation of fresh and unweathered rock surfaces by removing surficial deposits and weathered bedrock, which hide discontinuities and disguise lithology. Trenches may uncover solution channels, prove or disprove the existence of suspected faults, aid in identifying rock types, and locate ground water. Trenches and test pits also provide a means of obtaining samples for laboratory examination and tests. Trenches provide a continuous exposure along a given line and thereby disclose the continuity of strata.

4. Thin Sections, Microscopy - Thin section and other microscopic studies determine the mineral composition, texture, and structure in order to identify the type of rock and its origin. Crystal structure, determined by use of the petrographic (polarizing) microscope, identifies the minerals present in the rock samples, and provides data that aid in determining in-situ rock strength and stability. Microscopic studies would be used in initial stages of site selection to confirm stratigraphic correlations and rock conditions.

5. Paleontology, Micropaleontology - Identification of fossils in sedimentary rocks makes possible the construction of the strata's depositional history, which aids in understanding the regional geology. Fossil identification makes possible correlation of strata that cannot be correlated by lithologic characteristics alone. Paleontologic methods would be used during initial stages of site selection if needed to confirm stratigraphic relationships.

C. Ground-Based Geophysical Methods

1. Magnetics - Ground magnetic measurements, closely related to aeromagnetic surveys, are described in Section 2.1, describing aerial geophysical methods, and in Appendix A.

2. Gravity - Gravity measurements establish the earth's gravitational acceleration at designated points (Dobrin, 1960; Telford et al, 1976). Although some experiments have been performed with aerial and helicopter gravity surveys, terrestrial gravity surveys are the only type of survey to be considered for bedded salt repositories. Compared to magnetic surveys, gravity measurements are more expensive, but they are still much cheaper than seismic methods.

Sensitivity of gravimeters used in exploration is approximately 0.01 mgal. Factors other than subsurface density distribution which affect gravity measurements are elevation, terrain irregularities, latitude, and earth tides. Because the elevation and latitude of measuring stations must be known, surveying is needed for gravity measurements. This is a major item in gravity survey costs.

Two types of gravity surveys can be distinguished. Conventional gravity surveys for regional exploration usually employ station spacings of 500 m or more and are designed for an accuracy of 0.1 mgal. Surveying accuracies required are 30 cm in elevation and 100 m in latitude. Microgravity surveys (Omnes, 1975) use station spacings of 100 m or less, and achieve an accuracy of 0.01 mgal. Surveying requirements then become ± 3 cm in elevation and ± 10 m in latitude.

Tidal variations can amount to as much as 0.3 mgal. These variations are usually accounted for together with instrument drift by periodically reoccupying base stations. Terrain irregularities are difficult to eliminate, even if the topography is accurately known, because of uncertainties in estimating the density of near-surface rocks.

As opposed to magnetic measurements, gravity measurements are strongly influenced by changes in sedimentary rock. Salt, a low density material, is especially amenable to investigations by gravity surveys.

Variations in gravitational acceleration are of no direct interest for exploration and design of bedded salt repositories. Of interest are the density variations which cause local changes in gravity. These variations allow interpretation of the type and distribution of rocks in the subsurface. Interpretation of gravity maps is very similar to magnetic data interpretation. Using both types of data together increase confidence in the interpretation.

Gravity data provide information on rock types (both basement and sedimentary), depths to distinctive rock units, and on faults and lineaments. As in magnetic interpretation, depths calculated from gravity measurements are based on certain assumptions and are accurate to about ±10 percent. Some depth estimates have to be rejected because they do not conform to the assumptions used. Gravity measurements give only certain limits of the depth to a rock body causing an anomaly. Usually, the depth calculated is a maximum depth to the upper surface of the rock body.

Lineaments and circumferences of lithologic units can often be located to within 10 to 20 percent of the depth of rocks causing anomalies. Shallower features can be located more accurately than deeper ones. Gravity data are particularly valuable for finding indications of faulting. In petroleum exploration in sedimentary basins, gravity has been used effectively in conjunction with seismic reflection measurements.

Voids in bedded salt can be theoretically determined from gravity measurements. However, for the expected depths of repositories, the method--because of its limitations--is not suitable for this purpose. Voids in bedded salt will have to be investigated by seismic reflection and by radar measurements in boreholes and pilot shafts.

3. Seismic Refraction - Seismic refraction measurements consist of creating a seismic impulse by explosive or mechanical means and recording arrival times of refracted seismic waves along a line of measurement (Mooney, 1973; Musgrave, 1967). Straight lines fitted to distance (from shot point) vs. arrival-time plots permit calculation of seismic velocities for the different layers encountered. Locations of velocity breaks in the travel-time curve are used to calculate depths to interfaces. In this method, the distance between shotpoints and detectors (geophones) is large compared to the depth of seismic layers investigated; the horizontal distance needed is roughly three to five times the depth penetration.

Seismic body waves are either of the P- or S-type. Compressional or P-waves are always faster than shear or S-waves in a given medium. For this reason, P-waves are used exclusively in seismic prospecting, although experiments using S-waves have been performed and newer developments have made the use of S-waves in lithologic determinations potentially more interesting.

Seismic refraction is used primarily to determine seismic velocities and depths of near-surface layers. Such determinations are used not only for engineering purposes but also for corrections applied to seismic reflection surveys. In fact, seismic refraction investigations of shallow layers can be made part of a seismic reflection survey of the area.

The usefulness of seismic refraction measurements for bedded salt repositories is limited to near-surface investigation down to depths of a few hundred meters. As the depth increases, the method becomes more and more generalized and difficult to interpret. The refraction method depends on the assumption that seismic velocities increase with depth. If this assumption is not fulfilled, the method gives erroneous results. Also, with increasing shot-dectector lengths, increasing amounts of dynamite have to be used, adding to the expense of the survey.

Velocity--the main parameter derived from refraction measurements--is of direct interest to repository design. Seismic velocities are directly related to the dynamic elastic constants of a medium, and velocities can be used to characterize the rock and soil types encountered. Velocity also defines rippability for excavation purposes.

With reversed refraction profiles, depth and dip of subsurface layers can be calculated. Other methods of interpretation exist for determining variations in subsurface depth for each geophone location. Masuda (1975) provides a good summary of these interpretation methods.

4. Seismic Reflection - Seismic reflection measurements are performed by measuring travel times of seismic waves artificially generated at or near the surface that return to the surface after being reflected from subsurface horizons (Dobrin, 1960; Telford and others, 1976; Dix, 1952). Compared with seismic refraction, shot-to-detector distances are small compared to depths investigated, and smaller amounts of dynamite are needed per shot for a given depth penetration.

Again, in normal seismic exploration only P-waves are used. Some experiments with S-waves have been performed, and S-wave techniques are attracting renewed attention with respect to lithologic investigations.

Seismic reflection is by far the most expensive exploration method. However, it is also the most effective and most highly developed method which gives detailed and accurate information on subsurface layers, depths, velocities, faults, and cavities. New developments in data processing and interpretation have led to more definitive answers on the lithology of reflecting layers.

The reflection method requires extensive field operations and sophisticated computer processing. Problems that occur in this type of survey are related to variations in near-surface low-velocity layers, to accurate determination of velocity at depth, and to multiple reflections.

For purposes of nuclear waste repositories, two types of seismic reflection surveys must be distinguished:

- Standard reflection surveys for investigating sizable areas and depths

- High-resolution surveys for investigating specific, localized targets, usually at shallower depths. These surveys require shorter geophone group spacings, higher frequencies, and shorter sampling intervals in digital recording than the standard surveys.

Subsurface reflections depend on the acoustic impedance of rocks and soils. Acoustic impedance is the product of the density and velocity of the medium. Therefore, the reflection amplitude is influenced by both velocity and density, whereas the measured travel time depends on velocity and depth.

Parameters derived from measurements of reflection time vs. distance are velocity, depth and related parameters of bed thickness, and local relief or relative depth. In addition, amplitude measurements made on modern digital recordings define reflection coefficient (velocity times density) and attenuation characteristics.

Velocity is determined from the reflection hyperbolas by computer techniques. These schemes permit calculation of both average velocities to a certain depth and interval velocities (Dix, 1955). If the data are not distorted by steep dips, these velocities tend to be internally consistent and accurate to within a few percent. In order to arrive at an absolute estimate of the velocity, however, it is essential to have information from boreholes which can be used to calibrate estimates made from seismic records.

Velocity information from boreholes consists of velocity logs and well shots. Velocity logs show interval velocities as measured by an acoustic borehole probe. Well shots measure the average velocity from shots at the surface to detectors at different levels in boreholes.

With accurate velocity information, depths to reflective layers can be calculated. Although seismic sections are usually plotted in terms of reflection time, modern processing methods permit calculation and plotting of sections in terms of depth to provide an actual cross section of the subsurface.

Absolute depths can usually be calculated to within a few percent. Correlation with nearby well information may increase the accuracy to within 3 to 10 m (Dobrin, 1960). Relative depths can be resolved with the latter accuracy. In high-resolution surveys, an average situation will lead to the capability of resolving a 3-m-thick bed at a depth of 3000 m (Farr, 1979). Resolution is a function of depth and of sediment type. With increasing depth, higher frequencies are attenuated, resulting in decreased resolution. Sediment types can influence attenuation considerably; for instance, a shale section will permit far better penetration of high-frequency waves than a sand section (Farr, 1979).

Newer developments have led to inverted seismic cross sections which show velocity plotted as a function of depth (Savit, 1978; Garotta, 1978; Lindseth, 1979). This type of section permits closer correlation with subsurface lithology as obtained from boreholes and direct stratigraphic interpretation of seismic data.

Seismic cross sections provide a wealth of data on subsurface configuration, including faults and voids in, for example, salt or limestone. These structures are derived by interpreting the seismic cross section, and skill of the interpreter is a key factor in the quality of the interpretation. Voids may be indicated only by the presence of a diffraction pattern in the seismic section; however, if large enough, they may be completely resolved on a seismic section.

In spite of sophisticated methods used to attenuate multiple reflections, interpretation of the exact nature of a seismic horizon is still subject to critical evaluation by the interpreter.

5. Electrical and Electromagnetic Methods - Electrical and electromagnetic methods are used to measure the electrical resistivity of subsurface rocks. A great variety of methods exists; only a limited number among these are suitable for investigating bedded salt repositories (Keller and Frischknecht, 1966; Grant and West, 1965).

As is the case with the other potential field methods (gravity, magnetic), electric methods give only indirect indications of subsurface configuration. Except for features near the ground surface, they permit only generalized conclusions, and the validity of interpretations is strongly dependent on comparison with other data.

Electromagnetic methods (Vanyan, 1967), which are based on measurement of time-varying magnetic and electric fields, can be subdivided into methods using artificial sources and those using natural sources. Artificial sources, in general, do not provide sufficient depth penetration. Among the methods using natural sources, the magnetotelluric and audiomagnetotelluric methods are among the most effective (Cagniard, 1953; Kunetz, 1972). They use natural current fields related to ionospheric currents which, in turn, are induced by radiation of charged particles from the sun. These earth currents penetrate to great depth and, depending on the frequencies used, magnetotelluric measurements can provide resistivity estimates to depths of several thousand meters. The effective depth of penetration depends on resistivity and frequency. Lower frequencies provide greater penetration. Also of importance is the fact that the depth of penetration is greater in resistive strata such as salt beds.

Magnetotelluric measurements are particularly suited for reconnaissance surveys because the equipment used in the field is relatively small and easy to set up. However, for better definition of subsurface features, DC electrical resistivity methods are often advantageous.

Direct-current resistivity measurements are performed by applying a current into the ground through electrodes and measuring the resulting potential at certain points on the surface (Kunetz, 1966). Direct current or slowly alternating current is used in these measurements. Slowly alternating currents or periodic current reversals are used to eliminate polarization effects of the electrodes. Porous potentiometric electrodes are used with DC to prevent this problem.

There are many different resistivity methods based on different electrode arrangements. One of the most widely used methods is the Schlumberger configuration, which results in relatively good resolution and efficient field procedure. The Schlumberger configuration consists of two current electrodes and two potential electrodes symmetrically arranged on a line, with the potential electrodes near the center of the configuration. The distance between the current electrodes is much greater than the spacing of the potential electrodes, the minimum ratio being five to one.

Since reconnaissance electrical measurements over wide areas are not expected to add information to the detailed studies needed for repository siting, we recommend only the use of Schlumberger measurements, including their variants (namely, modified Schlumberger method and equatorial configuration), in the area of the envisioned site. For detection of fractures and resulting low-resistivity zones, magnetotelluric measurements may also be useful.

Electrical and electromagnetic measurements determine apparent resistivity as related to electrode spacing or frequency used. This information has to be interpreted to derive a measure of actual rock resistivity versus depth and location (Van Nostrand and Cook, 1966).

By using certain assumptions and mathematical procedures, resistivities and depths to interfaces between different layers can be estimated. Resistivity can often be determined with an accuracy of about 15 percent. Depth determinations are usually much less accurate.

As with other potential field methods, it is important to compare electrical measurements with other geological and geophysical information to arrive at an improved interpretation.

6. Microseismic Methods - Microseismic measurements consist of recording and analyzing acoustic signals that originate in and travel through the subsurface. There are two types of methods: rock noise monitoring and sensu stricto microseismic measurements.

Rock noise monitoring detects subaudible noise resulting from stress conditions or mass movements in the subsurface. Locations at which sounds originate can be determined by analyzing recordings made with several detectors distributed over an area. In geothermal exploration, this method has been used extensively to monitor ground noise that is often associated with geothermal reservoirs (Clacy, 1968; Teledyne-Geotech, 1972; Butler and Brown, 1978). Such noise may be caused by thermal stress or circulation of water or steam in the reservoir formation.

Other applications of this method include locating underground water flow, locating water leakage paths in dams and reservoirs, and analysis of failure conditions in structures and soil or rock slopes. Failure of slopes or underground cavities is usually preceded by rock noise emanations that increase in frequency up to the point of failure. Careful monitoring may permit taking remedial measures before a critical point is reached.

Microseismic measurements--sensu stricto--or microearthquake measurements, are a part of earthquake seismology. This type of measurement is performed by placing sensitive seismographs in various locations around an area to be investigated (Asada, 1957). The instruments are designed to record small earthquakes (less than magnitude 3) occurring in the area.

With a sufficient number of microseismographs, foci of such earthquakes can be determined and plotted (Lee and Lahr, 1972; Leslie et al., 1976). Movements producing small earthquakes are often generated by faults and local fractures. Given a sufficient length of recording time, locations of successive microearthquakes serve to define the location and attitude of faults or fracture planes (Brune and Allen, 1967; Combs and Hadley, 1977).

Additional information can be obtained from focal mechanism studies (Stauder, 1962). The direction of first motion of earthquake waves in an area defines quadrants of compression and dilatation (Nakano, 1923), each quadrant having a consistent direction of first motion. These quadrants are related to the initial motion of the P-wave created by the force system at the earthquake focus. The quadrants of alternate compression and dilatation are divided by nodal planes, one of which is the fault plane and the other an auxiliary plane (Gupta and Rastogi, 1976).

2.4 UNDERGROUND TECHNIQUES

A. Geologic Methods

The ultimate technique for the determination of subsurface geology is direct observation and mapping in shafts or adits. Because of the great expense involved, this method is normally reserved for the final stage of exploration to confirm geological information derived by other means and to provide access for in-situ rock mechanics testing.

Before excavation of shafts and adits is undertaken, the area should be investigated by exploratory drilling. The most commonly used method of exploratory drilling in bedrock is diamond core drilling because it is the most efficient method of obtaining representative samples of the rock as it exists in situ (Acker, 1974; Cumming and Wicklund, 1978). Other non-coring methods such as rotary drilling or down-the-hole hammer percussion drilling can be used to drill holes for photographic and television cameras, geophysical logging equipment, or installation of instruments. These non-coring drilling methods may also be used to penetrate overlying strata quickly and inexpensively until the level where diamond coring is recommended.

Diamond core drilling and associated techniques are discussed in this section along with some of the classification systems that are used to evaluate the quality of diamond drill cores.

1. Diamond Core Drilling - The two general methods of core drilling in common use differ in the way core is retrieved from the hole. In the conventional method all of the drill rods and the entire core barrel are removed from the hole at the end of each run. In the wireline method, the inner tube of the core barrel is removed through the center of the drill rods by a cable. The drill rods and outer core barrel remain in the hole until the hole is completed or it is necessary to change the diamond bit. The advantages of the wireline method are that

it is faster, particularly for deep holes, the core is less likely to be damaged as the rods are pulled, and the drill rods act as casing and prevent caving. The disadvantages are that it produces a smaller diameter core from the same size hole as the "conventional" method, and it is necessary to remove all of the rods from the hole to change the bit, thereby risking caving in bad ground.

All diamond drilling methods require a drill fluid to be pumped through the drill rods to the bottom of the hole to cool the bit and remove cuttings from the hole. The most frequently used fluid is water, sometimes with bentonite or soluble oil added. Compressed air is also used. The disadvantage of using water for drilling in soluble bedded salt is obvious. The problems associated with using air is that it is difficult to blow cuttings from deep holes, and any moisture in the hole will result in the formation of a mud cake which can prevent the discharge of cuttings.

Core recovery is influenced by the type of bit used and the type of core barrel. The selection of proper bit is greatly dependent upon the characteristics of the rock being cored, such as its solubility, hardness, and degree of cementation. The type of barrel most often used is a double tube swivel-type design in which the inner barrel does not rotate with the outer barrel and cutting bit. In highly fractured or loosely cemented rock, a triple-tube core barrel in which the inner tube is split lengthwise is highly recommended. With this barrel, the inner tube is removed and opened lengthwise to expose the core, thereby assuring a relatively undisturbed sample for study and photography.

Two methods used to obtain additional information from cores are

- Integral Coring - A specialized overcoring technique is used to recover badly fractured rock completely and with fracture spacing intact. A small-diameter hole is drilled and a steel rod is grouted into the hole. The rod is then overcored with a larger diameter bit and the rod and surrounding cylinder of rock are removed as a unit (Rocha, 1973).

The method is slow and difficult and not feasible for deep holes. A variation is a pre-grouting technique in which a small-diameter hole is drilled and pressure grouted before it is overcored. This method is not often successful and it is seldom used.

- Oriented Coring - Various instruments and techniques have been devised in an attempt to find a way of orienting a drill core in the same position that it occupied in situ (Goodman, 1976; Voloshin et al., 1968; Zimmer, 1963). The objective is to allow determination of the dip and strike of bedding planes and fractures. Mechanical, electrical, and magnetic methods have been attempted but no completely satisfactory system has yet been developed. Any attempt to obtain and utilize oriented cores, particularly from deep holes, should include a borehole survey.

2. Borehole Survey - Boreholes seldom follow their initial bearing and inclination. Even "vertical" boreholes drift and are seldom if ever plumb. A borehole survey plots the true inclination and direction of the borehole at frequent intervals so that its true location can be plotted. It is important to survey deep boreholes frequently if they are to be drilled near but not into a potential disposal area and if a reliable interpretation of the data derived from the hole is to be obtained.

3. Borehole Permeability Test - Another means of evaluating the permeability or degree of fracturing in rock that is normally performed in exploration holes is the water test (USBR, 1977). There are a number of variations of the borehole permeability test, including the Constant Head Test, the Falling Head Test, and the Pressure Test. The Constant Head Test measures the constant flow of water required to keep the hole full. The Falling Head Test (Gravity Test) measures the rate of drop of the

water level in the hole. In the Pressure Test, which is the most frequently used test in rock, sections of the hole are isolated by expanding packers in the hole and then water is pumped under pressure into the isolated zone. The pressure, rate of water loss, and length of hole tested is used to calculate the permeability of the formation.

Results of borehole permeability tests should be used with caution, as they are frequently in error by a factor of 10 or more. As water flow in rock is almost entirely through fractures; however, the water tests do provide at least a qualitative means of evaluating the degree of fracturing in rock.

4. Borehole Photography and TV - Photographic and TV cameras have been developed that can be lowered into boreholes three inches in diameter or larger (Trantina and Cluff, 1963). One of the cameras photographs the image on a conical mirror which gives a donut-shaped photograph of the circumference of the hole. Another camera takes a stereo photograph looking vertically downward. Calculation of true strike and dip is possible with the first type of photograph, but the second type allows only a visual estimate of approximate strike and dip. On one model of TV camera, the lens is directed downward onto an angled mirror that can be rotated from a surface control panel. Another model can be made to view axially, radially, or with a 180-degree lens opening (Winterkorn and Fang, 1975). It can also be fitted with a zoom lens and a powerful floodlight. The distance between objects observed with this lens can be estimated because the time required for focusing to various distances is known. Dips and strikes can be estimated and the TV images can be recorded on tape for more detailed study. In addition to allowing determination of the spacing and orientation of fractures, joints and bedding, borehole cameras allow inspection of zones of little or no core recovery. Their major disadvantage is that they do not work well and are subject to frequent malfunction in holes filled with muddy or oil-coated water.

Under ideal conditions camera surveys can give an understanding of subsurface conditions that is unobtainable by any other means except direct inspection in large diameter shafts and adits.

A related instrument is the borehole televiewer which presents a continuous acoustic picture of the borehole produced by a rotating ultrasonic scanner. The ultrasonic wave returns are converted into a visual image for viewing of borehole conditions. Fracture systems and the dip of fracture planes can be determined by this method (Zemanek et al., 1970). In order to obtain a good borehole picture, a slow and constant logging speed should be used and the solid content in the borehole fluid should be low.

5. Geological Analysis of Rock Samples - Analyses of samples by megascopic and microscopic methods provide information about the mineral composition, fossil content, texture, and structure. This information aids in determining how a rock mass will respond to construction operations and helps to correlate beds between boreholes to define the stratigraphic sequence and geologic structure.

Many micro-techniques are available for sample study, and generally employ either the petrographic or the binocular microscope. The petrographic microscope is used to identify minerals and to study thin sections. The binocular microscope is normally used to observe the larger features such as lithology, texture, and structure.

Micropaleontology is especially useful in evaluating structural conditions and facies changes, and in dating and correlating strata.

Megascopic examination of hand samples is often superior to microscopic examination for determining some rock properties. The color, texture, composition, and bedding are usually readily apparent when samples are observed megascopically.

6. Engineering Classification of Rock Masses - There have been many attempts to derive classification systems which would allow numerical values to be assigned to discontinuous rock masses (Deere, 1963; Bieniawski, 1974). Some of the parameters are strength of the intact rock material, degree of fracturing of drill core and fracture spacing, and condition and orientation of joints and fractures. Goodman (1976) lists several systems, two of which are described below.

One index, developed by Deere (1963), is the Rock Quality Designation (RQD), which is the ratio of the combined length of all hard and strong pieces of core 10-cm or longer to the total length of the core run. The RQD is one factor in the classification system proposed by Bieniawski (1974) which assigns a numerical value based upon uniaxial compressive strength of rock material, RQD, spacing of joints, condition of joints, orientation of joints, and ground-water conditions. Use of a standard classification system would allow a more meaningful comparison of various rock units at alternative sites than the general qualitative terms in use today.

7. Interpretation of Geologic Structural Data - Interpretation of geologic structural data is greatly facilitated by use of the descriptive geometry techniques of Badgley (1959) and the principles of stereographic projection and joint surveys described by Goodman (1976). Use of these methods allows interpretation of field data and solution of problems involving the relationship of formations, structures, lines and planes in space. Such problems are difficult to solve by other means.

B. Underground Geophysical Methods

Single Borehole Techniques (Well Logging) - Geophysical well-logging techniques test the earth with instruments lowered into boreholes; data are transmitted to recording devices at the surface. The logs give a detailed and continuous record of the borings and allow detection of subtle layer boundaries.

Qualitative interpretation of the logs enables determination of porosity, permeability, lithology, pore-water chemical quality, geologic structure, fracturing, fluid movement and distribution, and environment of deposition. Quantitative interpretation of porosity, permeability, and water salinity may also be performed. In addition, correlation of beds may be accomplished more easily with geophysical well logs than with other methods. By correlating the logs obtained from the wells of an area, a subsurface geologic map can be drawn showing faults, structures, and changes in lithology and sedimentation.

Geophysical methods that have been applied in well logging include electrical (self potential and resistivity), acoustic, nuclear, temperature, chemical, mechanical, and photographic. Generally, a standard ensemble of logs is run; the appropriate logging tools are selected according to the in-situ rock and soil conditions and the specific information required for the study.

In this report, borehole photographic and TV logging are covered in Section 2.4A, Underground Geologic Methods; temperature and thermal conductivity logging are covered in Chapter 5, Thermal Measurement Techniques.

The geophysical logs must be interpreted in conjunction with each other and with available core samples. Geophysical logs are made (by a field geologist, engineer, or technician) after drilling and core sampling have been completed. Depending on the method used, the borehole may be cased or uncased. For unstable soil or rock in uncased holes, the boreholes should be kept open using a material such as drilling mud during the logging operation. Drilling mud also provides an electrolytic medium between the downhole probe and the wall of the borehole if electric logging is performed. Drilling near salt domes can produce significantly increased borehole failure problems (Bradley, 1979).

1. Electrical Logging - The physical properties measured in electrical well logging are electrical resistivity and self (or spontaneous) potential. Self potential and resistivity were the earliest and are still the most frequently applied methods of borehole logging. An electric log consists of simultaneously run curves of electrical resisitivity and self potential. Such logs are valuable for correlation between wells and for subsurface mapping.

a. Self-Potential (Spontaneous Potential) Logging - Potentials in boreholes may be caused by a number of effects--e.g., streaming (electrokinetic) potential, shale (diffusion) potential, liquid junction, and mineralization. The principal effect encountered, however, is probably caused by electrochemical reactions occurring between the drilling fluid and the formation interstitial water (Wyllie, 1949).

Potential measurements are usually made by recording potential changes between an electrode in a borehole and another electrode at the surface. In some instances, the potential gradient is measured between two downhole electrodes positioned at small spacings. Potential and resistivity measurements are generally recorded simultaneously.

The density and resistivity of the mud can seriously affect the potential curve. When the drilling mud is very salty, the potential curve is flat and may be useless. This condition may obtain in the vicinity of a salt repository.

b. Resistivity Logging - The electrical resistivity of a fluid-saturated rock or soil depends mainly on the pore fluid conductivity, porosity, interconnection of voids, and bed thickness. In general, resistivity is inversely proportional to porosity and salinity. Usually, direct current or alternating current of low frequency is applied to current electrodes and the potential is measured between two or more potential electrodes. The result is a plot of apparent resistivity versus depth. Various techniques are discussed in Appendix A-7.

2. Acoustic Logging - Acoustic logs measure the elastic or seismic properties of rock and soil. In the acoustic logging method, sonic energy is generated by a transmitter in the boreholes, and transmitted to a receiver or multiple receivers. When the acoustic energy is recorded, identification can be made of four wave types. The first wave arrival is a compressional (P-) wave that travels in the rock surrounding the borehole. The second wave arrival is a shear (S-) wave that takes the same path. The third arrival is a fluid wave that travels through the fluid column in the borehole. The last (fourth) arrival is a Stoneley wave that travels along the area of contact between the well bore wall and the borehole liquid.

The principal applications of sonic logs have been in detecting fractures (King and McConnell, 1973) and determining porosity (Berry, 1959). Porosity can be determined using a standard formula that relates porosity to the wave velocity in the rock (formation) and the wave velocity in the fluid that fills the pore space (Wyllie et al., 1958).

3. Gravity Logging - Gravity logging is a relatively new method for determining the mean density and, accordingly, porosity of formations between gravity stations (Hammer, 1950). Depth of investigation is much greater than in other porosity logging methods, and measurements are not as strongly influenced by drilling effects. In addition, casing does not significantly affect the results.

More accurate density determination can be made with borehole gravimeters than with the other logging tools mentioned (Schmoker, 1978). Nearby density changes can be logged in material not penetrated by the borehole, such as density changes due to a salt dome or other geologic structures.

A number of instruments have been developed for gravity logging in boreholes (Howell and others, 1966). The mechanisms are similar to those used in surface measurements. The size of the borehole gravimeter may require a larger size hole than that used in most other logging techniques. The LaCoste-Romberg borehole gravimeter, for example, requires a hole with a diameter greater than 6 inches. Also, temperature and pressure may be limiting factors in the use of the instrument. Because of the cost of the instruments, they should be used in cased holes unless the holes are in excellent condition.

4. Nuclear Logs - Some atomic nuclei emit natural radiation and others can be induced to do so. Although several types of rays are emitted (alpha, beta, and gamma rays, and neutrons), only gamma rays and neutrons have enough penetration to be of practical use in logging.

Well logging instruments are basically of three types: (1) those that detect gamma radiation from the natural radioactive decay of uranium (U), thorium (Th), and potassium (K) in rocks; (2) those that use artificial gamma rays; and (3) those that induce nuclear processes using neutron sources.

All natural rocks contain some radioactivity due to the presence of U, Th, and K^{40}. Radioactivity is generally lowest in basic igneous rocks, intermediate in metamorphic rocks, and highest in some sediments and granitic rocks. Shales, clays, and marls are generally several times more radioactive than sandstones, limestones, and dolomites. In a given area, the radioactivity of shales does not vary much, so that a gamma-ray log is an approximate measure of the amount of shale in the formation.

The energy spectra of U and Th are broad, although there are characteristic gamma rays from Th (2.62 MeV) and U (1.7-1.8 MeV). The gamma ray from K^{40} is monoenergetic at 1.46 MeV. Gamma-ray detectors sensitive to the appropriate narrow energy band can be used to distinguish the source of radiation.

The average energy of gamma rays is approximately 1 MeV. About half the gamma ray detected in a borehole originates within five inches of the wall of the hole. In sediments, the depth of investigation is on the order of one foot. The intensity of radiation is reduced by approximately one-third if the borehole is cased.

Formation properties can also be determined by the interaction of neutrons with atomic nuclei in the rock. Neutrons are slowed by elastic and inelastic collisions with nuclei. Characteristic gamma rays are emitted as the result of both types of collisions. In elastic collisions, emission of the gamma ray is the result of neutron capture. In inelastic collisions, emission of the gamma ray is the result of an excited energy state of the nucleus.

5. Nuclear Magnetic Resonance Logging - Methods of magnetic well logging include the magnetic field log, the susceptibility log, and the nuclear magnetic resonance log. These methods measure either the formation susceptibility or the magnetic field itself. Magnetic well logging has not been widely applied, and of the three methods mentioned the most applicable to this study is the nuclear magnetic resonance log.

Nuclear magnetic resonance logging utilizes the principle of the nuclear precession magnetometer, which is described in Appendix A.1. The unbound hydrogen nuclei in the formation fluids are initially oriented by a strong magnetic field. When the field is cut off, the nuclei precess about the earth's magnetic field. The precession sets up an alternating magnetic field that induces a voltage in the receiving instrument. The amplitude of the signal is an indication of the unbound hydrogen in the formation and, accordingly, its water content. Porosity and permeability measurements have been obtained by this method.

6. Radar Logging - Ground-probing radar is a relatively new geophysical method which is still essentially in the developmental stage. The depth of penetration is determined by propagation attenuation in the medium under investigation and the properties of the radar system itself. Radar measurements outside salt domes have been restricted primarily to depths of approximately 10 meters. However, discontinuities in salt domes caused by anhydrite stringers, shale, sandstone, or fractures cause radar reflections that have been located to a depth of several hundred meters (Stewart and Unterberger, 1976).

Although borehole radar has not yet been widely applied, it may prove an exceedingly valuable tool for locating faults, fractures, voids, and caverns because of its much greater potential depth of investigation than other methods cited (Cook, 1977). Very-high-frequency (VHF) radar probing for discontinuities in salt were made from a drillhole by use of a 230-MHz-pulse radar well logging system (Holser et al., 1972). Hluchanek (1973) used a 440-MHz-pulse radar system to investigate the Hocksley Salt Dome.

7. Caliper Logging - Caliper logging provides a continuous recording of borehole diameter versus depth. The caliper has three arms that can be controlled from the surface.

Caliper logging is a valuable tool, since it is the only direct measurement of the in-situ rock condition. The logs are used to determine borehole diameter, to locate caved zones, to identify fractures, and to correlate geologic boundaries. Other geophysical logging methods can be correlated with the caliper logs to enhance the interpretation of the data and to obtain direct correlation with the actual physical rock condition.

Crosshole Methods - Logging methods which are based on a source-receiver measurement and have sufficient penetration can also be used in multiple borehole configurations. In this case, a source is placed in one borehole and receivers in one or more adjacent boreholes. Borehole measurements that can be applied to crosshole techniques include radar, electrical resistivity, acoustic, and shear wave.

Information obtained by the crosshole method is often more accurate because borehole effects can be minimized. Representative values of test parameters can be obtained by testing a much larger volume of undisturbed material. Measurement parameters obtained by crosshole methods include lithology, permeability, and fracturing. In addition, crosshole shear-wave measurements are particularly valuable in determining dynamic elastic parameters of rocks and soils.

1. Shear-Wave Measurements - In the crosshole shear-wave method, a seismic impulse is created at a given elevation in one borehole, and wave arrivals are detected at the same elevation in an adjacent borehole. It has been found that this method gives more accurate results and more detailed information concerning layers or fractured zones than other acoustic measurements, either in single boreholes or in uphole and downhole configurations (Mirafuente et al., 1974).

Crosshole shear-wave measurements will be needed during the site selection (A) and testing and design (B) phases of a bedded salt repository. They will give detailed and accurate elastic parameters for repository design, particularly with respect to earthquake loading conditions. During Stage B, these measurements should be obtained from the actual repository location at depth. Since present instruments are limited to a depth of about 150 m, either a modified instrument will have to be constructed for greater depths, or measurements can be conducted in boreholes drilled at depth from a pilot shaft.

Processing of crosshole shear-wave data is straightforward, and little or no interpretation is needed. Travel time of shear waves divided by the distance between boreholes gives the shear-wave velocity directly. The velocity can then be converted to dynamic shear modulus, if an estimate of density is available. Simultaneous measurement of compressional wave velocity also permits determination of Young's modulus, Poisson's ratio, or any other cynamic elastic constant.

Amplitudes of recorded shear and compressional waves can be used to determine absorption characteristics of materials. These characteristics give additional information on rock quality and fracturing.

Crosshole shear-wave velocity measurements are not only used to determine rock qualities for repository design, they also serve as a baseline for monitoring repository behavior under thermal stress. Repeated shear-wave measurements after waste emplacement will indicate any changes that may have been induced during repository operation.

2. Resistivity Measurements - With two or more boreholes available, current electrodes can be more widely spaced in one borehole and potential electrodes placed in adjacent boreholes for DC resistivity measurements. Better three-dimensional distribution of measuring points and more representative bulk measurements are thus obtained. Some resolution of layers and details is lost with this arrangement, and interpretation methods are not as sophisticated as those for single-borehole methods. Nevertheless, compared to single-borehole methods, crosshole resistivity measurements give better definition of bulk rock resistivity, with diminished capability for detecting local variations.

Electromagnetic measurements in crosshole configuration, in general, have the same advantages and disadvantages described above. Additionally, there is a problem in constructing sources for borehole use with sufficient capacity for penetration. Crosshole electromagnetic measurements, therefore, have not been used very much.

3. Radar Measurements - In a crosshole configuration, radar measurements will rely on radar transmission rather than reflection. Therefore, it should be possible to reach greater distances between transmitter and receiver than between a single borehole transmitter/receiver and reflectors in the subsurface.

Resolution of voids and other discontinuities is a question of frequency. Present methods can detect a tunnel if its diameter is equal to or greater than half the wavelength of the electromagnetic wave used (Lytle and others, 1979). This means that, for small voids, frequencies in the mega-Hertz range are needed. Such measurements, although they are still electromagnetic in nature, are usually called radar measurements.

Crosshole radar measurements indicate fractures, voids, or materials other than salt as shadows. With a good distribution of boreholes, it may be possible to delineate zones with such features.

Subsurface Mine Techniques - Essentially, all geophysical techniques that can be performed at the surface can also be applied to subsurface mines and tunnels. Subsurface mine techniques may offer better resolution of the physical parameters under investigation than surface methods because of the proximity of the area of interest. Subsurface tunnel and mine methods that have been applied in the past have included primarily seismic refraction and electrical resistivity measurements (Scott et al., 1974; Daeman, 1977).

Subsurface electromagnetic detection and ranging methods (radar) of geologic structure have recently attracted much attention. The ranging systems differ in the signal transmitted (either a particular radio frequency or an impulse), the antenna used to couple the electromagnetic energy to the rock, and the processing of the received signal. Selection of the transmitted signal and the antenna depends on the media involved, and the electromagnetic pulse must be designed for the particular application (Moffatt and Puskar, 1976).

All successful ground-probing radars at present employ electromagnetic waves of low frequencies (15-500 MHz) for maximum penetration (Cook, 1975). The waves are emitted in broad-band pulses of very short duration (2 to 70 nanoseconds) to obtain good discrimination of reflectors. Average transmitted power levels are generally only a few Watts, and equipment has been designed to be highly portable.

The rate of attenuation and velocity of propagation of an electromagnetic wave is dependent on the electric permittivity and magnetic permeability of the material. Although radar penetration is highly limited in most materials, radar transmission in salt to depths of several hundred meters has been achieved (Stewart and Unterberger, 1976). Low attenuation exists for pure salt at frequencies of 10^6 to 10^9 Hz. Impurities in the salt increase its attenuation rate. Also, saturated saline solutions have a high conductivity, and attenuation may be severe for radar waves travelling through wet rock salt.

A reflection of the radar energy in salt occurs when discontinuities in the electric permittivity or magnetic permeability are encountered. These discontinuities and subsequent radar reflections may be caused by sandstone, shale, anhydrite, water, or fractures. Since electric permittivity varies rapidly with density, radar reflection could also be caused by variations in the salt density.

Stewart and Unterberger used a VHF radar system with a frequency of 440 MHz in the Cote Blanche Salt Dome to probe for the top and flanks of the salt. Many discontinuities were detected in a shear zone, and information about the salt roof was obtained by their method.

2.5 SUMMARY AND CONCLUSIONS

Geological and geophysical measurements often require considerable interpretation and it is frequently necessary to assume a continuity of conditions between the location where the measurements are made and the location where the information is needed. Such an assumption may be necessary in the case of a bedded salt repository site because it is important to maintain the integrity of the containment media; drilling a large number of exploratory holes may be precluded. Development shafts and adits will serve as exploratory tools to provide data for final design; provision should be made for modifications to accommodate conditions that are actually encountered.

Remote sensing is a valuable tool for geological mapping of the earth's surface. It provides a rapid means of economically acquiring regional information. The results, however, depend upon geologic interpretation and the correlation with data obtained from other sources, such as ground measurements. The completeness and quality of a photogeologic study will depend upon the photography used, the area studied, and the personnel involved. Because the information that can be obtained from remote sensing interpretation will vary with the scale of the photography, it is often advantageous to use both large- and small-scale photographs to ensure that neither small features, visible only on large-scale photographs, nor subtle regional features, apparent only on small-scale photographs, will be overlooked. The imagery acquisition techniques can be selected to obtain the best information based on conditions at the site.

Photogrammetric instrumentation may be used to reduce the precise field measurements that will be required, but the extent of photogrammetry that will be possible depends upon the area and the quality of photography that is available.

Since the major cost in borehole geophysics is drilling the borehole, it is recommended that as many borehole techniques as feasible be run in the test boreholes. Each method can add to the value of the total information obtained and methods should be correlated to enhance the information. The effectiveness of the borehole methods depends on a variety of in-situ conditions, including the type of borehole fluid, whether the holes are cased, the solubility of the salt in the borehole fluid, and rock lithology. The methods should be evaluated in the field and, if a method proves ineffective, alternatives recommended.

Important information obtained from self-potential and resistivity logs includes porosity, permeability, fracturing and geologic correlation. In addition, induction logs give information on geologic structure and formation dip.

With the exception of focused-current logs and induction logs, the electric logging methods described have serious limitations. Salt in the vicinity of the repository could increase the salinity of the drilling mud and, accordingly, its conductivity. Conductive drilling muds have a large influence on logging results and can render the methods ineffective. This shortcoming may be somewhat remedied by using either a logging electrode of much greater diameter or buffers above and below the electrode. Focused logs such as focused current logs or induction logs may be more effective in saline conditions. Induction logs can also be used in dry holes.

Each method mentioned provides its own unique addition to the data. Virtually all the borehole logs may be used alone to provide maps of soil boundaries and stratigraphic units. A combination of logs adds a confidence factor to the measurements, especially if they are sensitive to different physical parameters.

TABLE 2-1

Sheet 1 of 15

GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1]	Remarks
Geologic Structure, Stratigraphy, Lithology	AIRBORNE TECHNIQUES			
	A. Remote Sensing Methods			
	Conventional aerial photography	Determine formation outcrops and geologic structure	A	Complements surface studies, particularly with respect to structure. (See Footnote 2) (Miller, 1961; Ray, 1960)
	Low sun-angle photography	Locate lineaments and faults	A	Optional procedure for locating faults. (Walker and Trexler, 1977; Cluff and Slemmons, 1969)
	Satellite imagery	Determine stratigraphy and structure	A	Defines broad regional geology. (Sabins, 1978)
	Thermal infrared imagery	Determine temperature and surface water circulation. Outline geologic and structural units	A	Provides geological and structural information in addition to surface temperature variations related to circulation in upper aquifers. Detect faults by effect on ground water and vegetation. (See Footnote 2) (Sabins, 1978)
	Side-Looking Radar (SLAR)	Define structure and lineaments	A	Detects faults and fracture zones.
	B. Geophysical Methods			
	Gamma Ray Radiometry and Spectroscopy	Determine formation outcrops, and faults, radiation background levels	A	Used to acquire geological information and to detect faults. (Reeves, 1975)
	Aeromagnetic survey	Determine structure lineaments and basement depth	A	Conventional magnetic survey defines basement structure, depth, lithology, and lineaments. Comparisons with surface geology give information on structures that are influenced by basement configuration. High-sensitivity magnetic survey may detect salt structures. (Dobrin, 1960; Telford, et al., 1976)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

2/ Also applicable to ground-water studies.

TABLE 2-1
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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Location	GROUND-BASED TECHNIQUES			
	A. Geodetic Methods			
	Reference marker	Locate measurement position	A	Concrete pillar set in poured concrete. The top of the pillar is set flush with the ground and the referenced position is located with a brass marker. (ASCE, 1940)
	Permanent bench mark	Locate points of known elevations	A	Brass disk set in stone or concrete and marked with the elevation above mean sea level.
	Triangulation station marker	Locate control position	A	Brass disk set in a cylinder of concrete poured in place. For important control positions the surface monument should be supplemented by a substructure with a subsurface mark. (ASCE, 1940)
	Bedrock monument	Precision monitor bedrock movements	A	Standard steel pipe set in hole drilled in bedrock and backfilled with concrete. The upper portion is isolated from contact with the surface soil and weak, weathered rock. The top of the pipe is fitted with a stainless steel cone dimensioned to receive the standard extension rod. (O'Rourke et al., 1977)
	Plane table	To map rapidly	A, B	The table is mounted on a tripod and an alidade is used to take stadia readings. Measurements are plotted immediately. Work can be checked in the field. Good for reconnaissance work and rough surveys.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Location (Cont'd.)	A. Geodetic Methods (Cont'd.)			
	Traversing	Locate positions of points on the ground	A, B	A well-developed procedure consisting of distance and direction measurements to fix positions. Open traverses are used for exploratory purposes. For more precise work, closed traverses are employed, with angles measured by repetition, and distances taped forward and back. (Precision: 1/1,000 to 1/10,000)
	Trilateration	Locate positions on ground	A, B,	Similar to triangulation, but lines instead of angles are measured. The advent of electronic distance measurement makes this method feasible. (Stipp, 1962)
	Photogrammetry • Aerial photogrammetry • Terrestrial photogrammetry	Locate positions on ground	A, B	A stereo comparator is used to view overlapping photographs. By means of references to properly identified ground control points, the positions and altitudes of selected points can be discerned. The standard error of measurement is 1/9,000 to 1/50,000 of the width of image. (Gould and Dunnicliff, 1971)
Horizontal Control				
	Odometer	Measure distance	A, B	Useful for reconnaissance and rough planning (Precision: 1/200). For this and the following survey-related techniques, refer to McCormac (1976), and the standard works by Breed and Hosmer (1962, 1977).
	Tacheometry	Swift, indirect method to measure distance	A, B	Commonly used for mapping and rough surveys. Also for checking more precise work. (Precision: 1/250 to 1/1,000)
	• Stadia method		A, B	Telescope equipped with horizontal cross-hairs is sighted on a leveling rod and the intercepts read, from which the distance is computed.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.
2/ Also applicable to ground-water studies.

TABLE 2-1

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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Horizontal Control (Cont'd.)	A. Geodetic Methods (Cont'd.)			
	Tacheometry (Cont'd.)			
	• Subtense bar method	Measure distance	A, B	Distance is computed by sighting on a horizontal bar of known length and measuring the angle subtended. Can be used when rough terrain makes taping infeasible. (Precision: 1/1,000 to 1/5,000)
	Ordinary Taping	Measure distance with a graduated steel tape	A, B	Used in ordinary land survey. (Precision: 1/1,000 to 1/5,000)
	Precision Taping	Apply standard corrections to taping to improve accuracy	A, B	Uses standard steel tape, but tape tension carefully controlled; tape temperature is measured and appropriate corrections are applied. Excellent for land surveys. (Precision: 1/10,000 to 1/30,000)
	Base Line Taping	Measure distance with extreme accuracy using an Invar tape and following stringent procedures	A, B	Used in geodetic surveying. (Precision: 1/175,000 to 1/1,000,000). (Cf: National Geodetic Survey)
	Electronic Distance Measurement (EDM)	Measure distance by travel time of light waves	A, B	Can be used in ordinary land surveys and precision surveys. (Precision: ±0.04 foot; ±1/300,000) (Gould and Dunnicliff, 1971)
Vertical Control	Aneroid Barometer (Altimeter)	Determine elevations by measuring air pressure	A, B	Sufficient for preliminary or reconnaissance work. (Accurate within 10 to 20 feet).
	Dumpy Level	Level	A, B	High powered telescope attached to a level tube. Simple and dependable. Suffices for most leveling work.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 2-1

GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Vertical Control (Cont'd.)	A. Geodetic Methods (Cont'd.)			
	Tilting Level	Level	A, B	The telescope is brought to a level position quickly by means of a tilting knob. Permits faster and more precise leveling.
	Self-Leveling Level (Automatic Level)	Level	A, B	The instrument automatically does the fine leveling. Excellent on soft yielding ground and/or in strong winds.
	Differential Leveling	Measure vertical distance	A, B	Leveling precision can be increased by shortening sight distances, balancing backsight and foresight distances, and reading the level rod to the nearest 0.001 ft.
	• Second order			Error in inches not to exceed $0.035\sqrt{M}$ where M = miles leveled
	• Third order			Error in inches not to exceed $0.05\sqrt{M}$
	• Fourth order			Error in inches exceeds $0.05\sqrt{M}$
	Precise Leveling (First Order)	Measure vertical distance	A, B	Highest precision leveling as practiced by National Geodetic Survey. (Error in inches must not exceed $0.017\sqrt{M}$)
	Reciprocal Leveling	Measure vertical distance	A, B	A useful technique for increasing accuracy of leveling across wide or large bodies of water. Precision is further enhanced by using two levels and taking simultaneous observations from both sides.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

2/ Also applicable to ground water studies.

TABLE 2-1
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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Vertical Control (Cont'd.)	A. Geodetic Methods (Cont'd.)			
	Laser Beam	Provide reference line or datum	A, B	Alignments and grading can be controlled easily and accurately using either a fixed or rotating level beam.
Angles and Directions	Brunton Compass	Measure magnetic bearing of a line of sight, measure vertical angles and grade	A, B	A combination compass, clinometer, and hand level, with a wide variety of uses in reconnaissance survey and geologic field work.
	Transit	Measure horizontal and vertical angles	A, B	Versatile instrument used to measure angles, prolong straight lines, perform leveling, determine magnetic bearings, and measure distance by stadia. (Precision: 10 sec to 1 min of arc)
	Theodolite	Measure horizontal and vertical angles	A, B	Similar to transits, but more precise, and readings are taken through an eye piece located near the telescope. (Precision: 1 sec to 6 sec of arc)
	Photo-Theodolite	Take terrestrial photographs	A, B	Theodolite mounted on a survey camera to facilitate taking stereo pairs. Used in conjunction with photogrammetric methods. Requires ground control points.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.
2/ Also applicable to ground-water studies.

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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Ground Deformation	A. Geodetic Methods (Cont'd)			
	Tape Extensometer	Precision measure linear deformations	B, C, D	A high quality steel tape with holes punched at regular intervals to engage a displacement dial gage. Distance is measured by adding the dial gage reading to the distance shown on the punch mark. Tension adjustment and temperature correction required. Precision: 1/75,000 to 1/180,000) (O'Rourke et al., 1977; Cording et al., 1975)
	Micrometer Beam Extensometer	Precision measure linear displacements	B, C, D	A rigid beam extensometer fitted with a micrometer and a tiltmeter can measure changes in vertical and horizontal distances between neighboring monuments with high degrees of precision. Simple and relatively inexpensive. Ideal for monitoring bedrock movements over short range. (Precision: 1/200,000 to 1/300,000) (O'Rourke et al., 1977; Cording et al., 1975)
	Tiltmeter	Measure tilt angle	B, C, D	A precision spirit level equipped with a micrometer adjustment is used either singly or with a rigid beam extensometer to measure tilt angles. Precision lines using tiltmeters are employed to monitor ground movements across faults or fractures, and to profile ground subsidence. (Precision: 1/20,000 to 1/200,000) (O'Rourke, et al., 1977; Panek, 1970)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.
2/ Also applicable to ground-water studies.

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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Ground Deformation (Cont'd.)	A. Geodetic Methods (Cont'd.)			
	Beaver Inclinometer	Measure lateral movement underground	B, C, D	A null-balance accelerometer mounted inside a probe senses the component of earth's gravity along its axis. The equipment is designed to collect and record data automatically in IBM compatible format for computer processing. Operates at any angle from vertical to horizontal. (Precision: 1/1,000 to 1/5,000) (Bromwell et al., 1971)
	Multiple Position Borehole Extensometer (MPBX)	Measure strain gradients or displacements in the soil or rocks	B, C, D	Several designs are available, including rod, wire, and probe types. A recent development that holds the most promise consists of permanently installed circular magnets anchored to the walls of an uncased borehole and a reed-type switch acting as a sensor. An optional micrometer drive head located at the top of the extensometer provides very accurate positions of the switch. Reliable and relatively inexpensive. (Precision: 0.5 mm to 0.2 mm). (Burland et al., 1972; Cording et al., 1975)
	Terrametrics Portable Borehole Deflectometer	Continuously measure angular variations along the axis of a borehole	B, C, D	A pivoted joint between the deflection-arm head and the guide housing allows the deflection-arm to deflect with respect to the guide housing. As the instrument is moved up or down the cased borehole, transducers pick up the angular variation and a continuous profile is obtained. (Cording et al., 1975)

1/ Repository Development Stage: A = Site Selection, B - Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

2/ Also applicable to ground-water studies.

GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Ground Deformation (Cont'd)	A. Geodetic Methods (Cont'd.)			
	Borros Anchor Point Settlement Probe	Measure near-surface displacement (vertical)	B, C, D	A conical steel drive point with retracted steel prongs is lowered to the required depth in a borehole and the prongs are forced into the ground. An outer casing protects and isolates the inner rod from drag due to settlement of the ground above the point. Requires leveling. (Cording et al., 1975)
	Deep Ground Settlement Probe	Measure deep-seated ground displacement (vertical)	B, C, D	A cased borehole is advanced by any conventional method to the depth to be monitored. If the casing is placed in a predrilled hole, the annular space must be grouted. Hydrostatic pressure must be balanced by drilling mud to prevent bottom blowout during boring. The inner probe is secured to the strata at bottom of the hole. A few feet of embedment is usually adequate. For more secure anchorage, grouting should be done. (Cording et al., 1975)
	Wilson Slope Indicator	Measure underground horizontal movements	B, C, D	A sensor placed in a flexible casing in the ground detects lateral movements by measuring at various depths the deviation of the axis of the probe from the true vertical. (Precision: 1/1,000 to 1/2,500) (Wilson and Hancock, 1965)
	Hydraulic Piezometer	Measure pressure head (Changes in head can indicate ground deformation)	A, B, C, D	Hydraulic piezometers require comparatively large amounts of flow in and out of the porous tip to adjust to the changes in external head and should be used only in more pervious strata to reduce hydrodynamic lag time.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization

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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Ground Deformation (Cont'd.)	A. Geodetic Methods (Cont'd.)			
	Hydraulic Piezometer (Cont'd.)			
	• Casagrande type			Long an industry standard in the geotechnical field, it requires careful installation. (Casagrande, 1949)
	• USBR type			Also called a closed system, it requires a fluid-filled line to transmit the external pressure to a measuring device located outside. Usually uses a second line to flush out trapped air or gases. (U.S. Bureau of Reclamation, 1974)
	Diaphragm Piezometers	Measure pressure exerted on the diaphragm by the interstitial fluid	A, B, C, D	The pneumatic type requires back pressure to exactly balance the external fluid pressure. Enables in-situ calibration. The electrical sensor type uses strain gage or displacement transducers to convert diaphragm deflection to piezometric head. The diaphragm units have quick response, but are prone to malfunctioning. (Schmidt and Dunnicliff, 1974; Cording et al., 1975)
Geologic Structure, Stratigraphy and Lithology	B. Ground-Based Geologic Methods			
	Surface Geologic Mapping	Determine rock units, structure, and stratigraphy	A	Provides geologic framework for repository by identifying outcrops and surface features. (Lahee, 1941)
	Joint Mapping, Fracture Analysis, Lineament Studies	Determine orientation and frequency of joints and lineaments and characteristics of fracture surfaces and infilling material	A	Used to analyze 3-dimensional distribution of fractures and to determine ground-water movement. (Hoek and Bray, 1974)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization

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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Geologic Structure, Stratigraphy and Lithology (Cont'd.)	B. Ground-Based Geologic Methods (Cont'd.)			
	Trenching	Determine fault and fracture locations, soil profile, ground water, expose bedrock	A	Serves to prove or disprove existence of near-surface active faults.
	Thin Sections, Microscopy	Determine mineral composition, texture, structure for lithologic correlation	A	Identifies mineral composition and texture which can be used to identify rock type and origin. (Leroy and Crain, 1949; Leroy, 1951)
	Paleontology, Micropaleontology	Determine age of rocks		Identifies fossils to determine age and history which aid in understanding regional geology. (Leroy, 1951)
	C. Ground-Based Geophysical Methods			
	Ground Magnetic	Locate magnetic anomalies	A	Detects near-surface faults, and indicates regional geologic trends. (Aitken, 1961; Breiner, 1973)
	Gravity	Determine basin structure, faults, salt depth	A	Salt is a low density material. Gravity variations indicate salt structure and faulting. (Dobrin, 1960; Telford et al., 1976)
	Seismic Refraction	Determine attitude of subsurface layers	A	Defines sequence and characteristics of subsurface layering. Can detect arrival-time delays caused by Holocene faults. Good reconnaissance technique. (Mooney, 1973; Musgrave et al., 1967, Masuda, 1975)
	Seismic Reflection • Standard	Determine subsurface structure, faulting, depth and thickness of strata, lithology	A	Most advanced method for defining subsurface structure. Conventional survey for regional structure and faulting. High-resolution survey for detailed definition of site conditions. (Dobrin, 1960; Telford et al., 1976; Dix 1952)

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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Geologic Structure, Stratigraphy and Lithology (Cont'd.)	C. Ground-Based Geophysical Methods (Cont'd.)			
	Seismic Reflection (Cont'd.)			
	• High Resolution			(Farr, 1979; Wiles, 1979)
	Electrical and Electromagnetic	Investigate structure and ground water	A	Defines gross layering of bedding and identifies leached cavities, if present.
	• General			(Keller and Frischknecht, 1966; Grant and West, 1965)
	• DC Resistivity			(Van Nostrand and Cook, 1966; Kunetz, 1966)
	• Electromagnetic			(Cagniard, 1953; Vanyan et al., 1967; Kunetz, 1966)
	Microseismic	Locate epicenters and fault trends and local stress fields	A	Monitors seismic activity, if present. May define faulted areas that are unsuitable for repositories.
	• Microseismic			(Asada, 1957; Brune and Allen, 1967)
	• Ground Noise			(Teledyne/Geotech, 1972)
	Emanometry	Measure radon level		Method to determine presence of fractures. Changes in radon level may indicate subsurface stress changes.

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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Geologic Structure, Stratigraphy and Lithology (Cont'd.)	UNDERGROUND TECHNIQUES			
	A. Geologic Methods			
	Core Drilling and Sampling	Determine stratigraphy and lithology, structure, fractures, rock quality	A, B	Permits accurate definition of subsurface layering and structure. Provides access for other geologic and geophysical methods.
	• Oriented Cores	Determine orientation of fractures and bedding		Permits definition of strike and dip.
	• Integral Coring	Obtain samples in loose or fractured rock		Permits sampling in formations that normally will not yield cores.
	Core Indexes	Determine rock strength	A, B	Core indexes give indication of probable rock stability around opening.
	• RQD (Rock Quality Designation)	Assess rock quality		Percentage of core in intact pieces over 4" in length is approximately related to the compressive strength.
	• Percent Recovery	Assess rock quality		Percentage of total core run that is recovered helps to determine rock strength, and adequacy of exploration.
	• Longest Piece	Assess rock quality		Longest solid core specimen recovered in total sample run of 10 feet indicates relative rock quality.
	• Joints Per Foot	Determine fracture density		Defines degree of fracturing in rock and salt beds.
	Geological Sample Analysis, Microscopy, Micropaleontology	Provide details on lithology and stratigraphy	A, B	Gives mineral composition, fossil content, and texture of individual rock and salt beds. Used to correlate beds between boreholes.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter		Measurement Technique	Purpose	Stage[1/]	Remarks
Geologic Structure, Stratigraphy and Lithology (Cont'd.)	A.	Underground Geologic Methods (Cont'd.)			
		Borehole TV, Photography, Televiewer	To determine fracture planes, bedding	A, B	Visual assessment of homogeneity of deposit and presence or absence of fractures or voids. (Winterkorn and Fang, 1975)
		Shafts and Adits	Map rock mass features	B	
	B.	Underground Geophysical Methods			
		Single Borehole Techniques	Provide information on:	A, B	These borehole logging methods provide information on lithology, porosity, permeability and fracturing of formations intercepted by boreholes. Interpretation of data is usually done by comparing different types of logs, particularly with respect to deducing fracturing. Used to correlate beds in areas where fine gradations between beds make correlation difficult. Also used to estimate parameters such as: porosity, density, and permeability.
		• Electrical Logging	Lithology, permeability, porosity, fractures		
		- Self-Potential			(Telford et al., 1976)
		- Resistivity			(Salt and Clark, 1951; Lishman, 1961)
		• Acoustic Logging	Porosity, fractures		(Guyod and Shane, 1969)
		• Gravity Logging	Density, porosity		(Howell, Heintz, and Barry, 1966)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

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GEOLOGIC, GEOPHYSICAL, AND GEODETIC MEASUREMENT TECHNIQUES

Repository Parameter	Measurement Technique	Purpose	Stage[1/]	Remarks
Geologic Structure, Stratigraphy and Lithology (Cont'd.)	B. Underground Geophysical Methods (Cont'd.)			
	• Nuclear logging			
	- Natural Gamma Radiation	Radioactivity, lithology		Gamma-Spectrometer. (Mero, 1960)
	- Density	Density, porosity		Gamma-Gamma Log. (Pickell and Heacock, 1960)
	- Neutron	Porosity, moisture content		(Pontecorvo, 1941)
	• Nuclear Magnetic Resonance (NMR) Logging	Permeability		(Brown and Gamson, 1960)
	• Radar Logging	Locate fractures, anhydrite stringers, and sand lenses		Dry salt is an ideal medium for radar transmission; large distances of penetration are attainable. (Holser et al., 1972; Stewart and Unterberger, 1976)
	• Caliper Logging	Borehole diameter		(Schlumberger, 1972)
	Crosshole Techniques	Provide information on:	A, B,	Application of crosshole methods is similar to that of methods used in single boreholes.
	• Acoustic and Shear Wave	Lithology, fractures, permeability, dynamic elastic parameters		Crosshole shear-wave measurements are particularly valuable to determine dynamic elastic parameters of beds between two or more boreholes. (Mirafuente et al., 1974)
	• Resistivity	Lithology, permeability, fractures		(ASCE, 1974)
	Mine Techniq.		A, B	All ground-based geophysical techniques can be applied in mines and tunnels. May offer improved resolution. (Stewart and Unterberger, 1976; Scott et al., 1974)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization

CHAPTER 3

ROCK MECHANICS

MEASUREMENT TECHNIQUES

3.1 INTRODUCTION

Rock stability within a repository is a major factor that affects the successful containment of nuclear waste. Floor heave, roof caving, pillar collapse, wall spalling, rock bursting, slip along joints and faults, borehole seal failures, shaft seal failures, and other variables may lead to the creation of leakage paths into emplacement areas. The ability to recognize and identify potential leakage paths requires a knowledge of stress-deformation characteristics of repository rocks. This knowledge can be obtained only by rock mechanics testing and measuring techniques.

The rock mechanics measurement techniques exhibited in Table 3-1 are divided into two broad categories, in-situ and laboratory, each having six subcategories. Each measurement technique is listed under the specific subcategory that best applies to the type of information produced. The arrangement below is followed in this chapter and in Table 3-1.

- In-Situ Measurement Techniques:
  - Stress
  - Stress Change
  - Elastic Moduli and Strength
  - Displacement
  - Tilt
  - Creep

- <u>Laboratory Measurement Techniques</u>:
  - Compression Testing
  - Shear Testing
  - Tension Testing
  - Fatigue Testing
  - Creep Testing
  - Other

In-situ measurements can also monitor rock mass behavior over time. The resulting data can indicate the physical state of a rock mass and of its associated supports.

Rock samples collected in the field are tested in the laboratory to provide basic information about the behavior of repository site rocks. These properties are determined exclusive of rock mass inhomogeneities such as faults, joints, and cavities. However, laboratory data aid in setting design parameters for underground workings and in establishing a baseline for the analysis of monitored data.

Rock mechanics techniques are designed to measure rock stresses, rock deformations, and the stress-deformation parameters that characterize the rock. The deformational response of a rock to an applied set of stresses will vary with rock type, the environment, and the internal state of the rock. Variations with rock type occur because of differences in the behavior of the rock's mineral components. Variations with the environment include the effects of temperature, the degree of dryness for dry rocks, pore pressure for saturated rocks, the presence of pore fluids other than water, and the presence of reactive chemicals. Variations with the internal state of the rock primarily include the degree and configuration of fracturing within the rock matrix resulting from previous states of stress and associated deformations. These factors complicate the full understanding of rock behavior for both in-situ and laboratory conditions. A discussion of stresses and stress-deformation behavior is presented in Appendix B.

Salt mine experience has shown that creep deformations can be expected in salt deposits. In general, the rates of creep around openings underground increase with depth (Hedley, 1967) and temperature (McClain, 1966; McClain and Bradshaw, 1970). Thus, to understand the mechanical behavior of pillars, rooms, and other openings over time, an understanding of the creep properties of the associated rocks is required.

Creep is normally defined as the slow, time-dependent deformation of a solid under application of constant stress. However, creep also can occur under changing stress conditions. The measurement of creep requires, then, the ability to measure stresses and displacements. All of the techniques described in Table 3-1 for stress measurement, stress-change measurement, displacement, and tilt can be adapted to programs for measuring and monitoring creep in a repository. A thorough discussion of creep laws, effects of pore water and internal fabric, and creep functions for salt can be found in Appendix B.

3.2 IN-SITU MEASUREMENT TECHNIQUES

A. In-Situu Stress Measurement Techniques

Three methods are used to determine the state of stress in a rock mass: 1) overcoring, 2) flat jacking, and 3) hydraulic fracturing.

1. Overcoring - Overcoring is the most flexible and useful of the three methods for determining rock stresses underground. In the overcoring method, deformations associated with a small-diameter hole are monitored as the rock around that hole is relieved by overcoring a larger, concentric hole. From these deformations, stresses are calculated with formulas derived from the theory of elasticity. In order to apply these formulas, the rock elastic constants must be known.

By drilling the pilot hole and then the overcore hole, the state of stress at a set of locations along a borehole can be obtained. Stress determinations can be made to depths exceeding 100 feet.

Three different types of measurement probes can be used to measure deformations in the pilot hole:

- Open-hole probe
- Hard-inclusion probe
- Soft-inclusion probe.

Open-hole probes measure the strain displacements in the wall of the borehole, or upon the flat end of the borehole during overcoring. Biaxial and triaxial measurements can be made (see Table 3-1). For the biaxial system, only stresses in the plane perpendicular to the borehole axis can be obtained for a particular borehole and these must be corrected for stresses acting parallel to the borehole (Panek, 1966).

To obtain a full state of stress, several specific cases must be considered. In an isotropic rock--i.e., a rock in which a given elastic constant is equal in all directions--the full state of stress theoretically can be obtained from a triaxial probe used in a single borehole (Oka and Bain, 1970), or from a biaxial system used in two, non-parallel, non-perpendicular boreholes (Panek, 1970). For orthotropic rock--i.e., rock with three orthogonal planes of elastic symmetry at each point--the full state of stress can be determined using the biaxial system in three non-parallel boreholes (Barla and Wane, 1970).

For a hard-inclusion probe, the probe modulus of elasticity must exceed that of the rock by a factor of at least 5.0 (Fairhurst, 1968). Large strains in the rock are resisted by the stiff inclusion so that distortions of the borehole wall are relatively small. The result is that the strains in the inclusion are dependent only upon the stresses in the rock and not upon the rock modulus (of elasticity) (Wilson, 1961; Hast, 1958). Strains in the probe are measured, and the stresses are calculated. Since the inclusion stresses are independent of rock modulus, the probe can be calibrated by placing it (the probe) in a metal cylinder and subjecting the cylinder to calibration loading cycles.

For a soft-inclusion probe, the probe modulus of elasticity must be less than that of the rock by a factor of at least 5.0 (Fairhurst, 1968). The inclusion distorts easily, offering little resistance to the deformations in the pilot hole wall. Strains in the inclusion are independent of the probe's elastic modulus and depend only upon the rock stresses and elastic constants (Agarwal and Boshkov, 1966). The inclusion is instrumented with strain gages which are monitored during overcoring. The strain data are converted into rock stresses by using appropriate elastic formulas. The inclusion elastic modulus, because of its small effect upon measured strains, can be neglected in stress calculations. The probe, therefore, does not have to be calibrated, but the rock elastic constants must be known.

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At present, the most commonly used probes are two open-hole biaxial units: the U.S. Bureau of Mines "borehole deformation gage" (or modification of it), and the South African "doorstopper" (see Table 3-1). These units are the simplest to use and have proven reliability. Hast's probe and the CSIR (Council on Scientific and Industrial Research, South Africa) technique have also been used successfully in hard rocks. The soft-inclusion probe developed by Rocha has been used in very deep boreholes, but operating problems have been encountered. All other gages (listed in Table 3-1) have been used primarily in hard rocks. There is a need for the development of a soft-inclusion gage for use in soft and fractured rocks.

Overcoring techniques are limited by the rock strength. If in-situ stresses are high, stress concentrations around the borehole perimeter may exceed the rock strength. This condition can lead both to a spalling of rock from the perimeter and to the development of discing in the overcore cylinders during drilling (Hast, 1979). If such spalling and discing develop, borehole deformations will no longer be purely elastic, and stress calculations based upon elastic theory will no longer apply.

Since rocks are highly anisotropic elastically, the use of isotropic equations to analyze stresses can introduce errors into the stress calculations. Anisotropic equations are available to calculate stress; however, the elastic moduli of the rock must first be determined (Becker and Hooker, 1967).

The accuracy of stress determinations by overcoring techniques is difficult to assess. In laboratory tests on blocks of rock, using the "doorstopper" probe, Leeman (1968) obtained stresses to within 10 percent of the applied stress and stress orientations to within 2 to 4 degrees of the actual orientations. Engelder and Sbar (1978) compared three methods of overcoring in sandstone and limestone. These methods included the "doorstopper" probe, the USBM Borehole Deformation Gage, and the bonding of strain gage rosettes directly to outcropping rock. Results of repeated tests showed that the precision of stress determination is seldom better than 20 percent in magnitude and ±10 percent in orientation.

At present, stress determinations better than 25 percent in magnitutude and ±10 percent in orientation cannot be expected for most applications of overcoring techniques. Accuracies for specific overcoring sites will vary with rock type and the condition of the rock. Accuracy also depends upon the skill and experience of the technicians performing tests. A research and development effort is required to determine the influences affecting accuracy and to improve probe performance.

2. Flat Jack Techniques - A flat hydraulic cell is placed into an open slot which has previously been cut into a rock face. The cell is then pressurized, forcing the steel membranes against the sides of the cut. The pressure required to return the rock to its virgin state is assumed to equal the rock stress acting normally on the flat jack. Deformation devices are used to measure strains across the slot and to determine when the virgin strain state is reached.

Flat jacks measure only the stresses normal to the jack. Several jacks can be installed to measure normal stresses in various directions. They have been used primarily to determine vertical stresses in mine pillars.

The accuracy of stress measurements with flat jacks have never been fully evaluated. Investigations into many areas are needed, including the effects of

- Jack length-to-width ratio
- Rock fracturing adjacent to jack slot
- Grouting media properties
- Cracking in the rock around the slot
- Residual rock stresses.

3. Hydraulic Fracturing (Hydrofracturing) - Hydrofracturing is a method of determining rock stress by causing the rock around a borehole to fail. Fluid is pumped into a sealed section of borehole until the borehole wall fractures in tension. Failure is recognized by a sudden reduction in slope of the pressure-flow rate curve. The minimum stress is then calculated from the fracture stress using standard formulas (Haimson, 1974). Stress orientation must be determined with borehole impression packers, borehole acoustical techniques, or other methods.

Hydrofracturing has been used extensively in the oil and mining industries for increasing the porosity of rock formations. It can also be used to determine approximate values for in-situ rock stresses at depth (Haimson, 1974, 1977). However, it is not an advisable method for determining in-situ stresses at a nuclear repository site because, by inducing rock fracturing, rock permeability will be increased.

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Support stresses must be monitored as well as the stresses of the rock mass itself. Load cells, flat jacks, and various strain measuring systems serve this purpose. For most support systems, the object of instrumentation is to monitor long-term stress increases at critical locations in the supports. The most common supports are props (compression members), roof bolts (tension members), steel ribs (either horseshoe shaped or circular), steel liner plates, steel precast liner segments, and poured and precast concrete linings.

Load cells can be used to measure compression and tensile stresses in bolts and props. Strain gages can be used to measure bending moments and axial stresses in all steel and concrete support systems. Flat jacks can be used to monitor pressure changes in mass concrete and in the contact between the rock and the supports.

Most supports are instrumented to monitor the stresses in the supports and not to determine the state of stress in the surrounding rock. However, increases in support stresses would indicate changes in loading and would indicate impending problems.

B. In-Situ Stress Change Measurement Techniques

Stress changes with time can be monitored by overcoring probes, borehole dilatometers, and pressure cells as indicated in Table 3-1. Stress changes can be caused by

- Mining excavations
- Pillar failures
- Roof failures
- Changes in the ground-water table
- Rock expansion due to heating
- Rock contraction due to cooling
- Other factors.

The analysis of stress changes is often a problem of determining the reason for the change.

Hard-inclusion gages have been used to monitor stress changes in pillars in coal mines (Wilson, 1961) and salt mines (Potts, 1964; Dreyer, 1977). A hard-inclusion gage has two advantages when used in rock susceptible to creep, such as salt. First, as mentioned earlier, a hard-inclusion gage will measure stress independently of the elastic moduli of the salt, thus making determinations of salt properties unnecessary. Second, the stresses measured by the inclusion will not be seriously affected by creep. If a rigid inclusion is placed in rock that is creeping at a constant rate, the stress level in the inclusion will be raised until stress equilibrium is reached between the salt and the inclusion. Thus, at equilibrium, the in-situ stress can be read directly without the need to correct for creep (Skilton, 1971).

Soft-inclusion stress monitoring systems include fluid-filled borehole sections, fluid-filled cylindrical cells for borehole placement, fluid-filled flat cells encased in cylinders of grout and placed in boreholes (borehole pressure cells, or BPCs), and fluid-filled flat cells placed in pre-cut slots. In all cases, rock stress changes cause changes in fluid pressure in the cells. Because a change in cell pressure tends to counteract the deformations induced by the rock stress changes, the cell pressure change can be related to a given rock stress change (Barr 1960).

For a flat cell fitted into a slot, almost all of the rock stress acting normal to the cell face is transferred to the fluid. Small stress differences are introduced by stress concentrations in the rock around the slot opening. If the fluid in the cell is stiff, it will reduce volume changes in the cell, and thus, reduce rock deformations around the cell. Keeping the rock deformations to a minimum keeps stress concentrations to a minimum so that cell pressure will more closely approximate rock stress. Stiff fluids are preferred for fluid cells (Ageton, 1967).

Glotzl cells are flat fluid cells designed to measure pressure at constant cell volume by use of a counter-pressure fluid system. Increases in rock stress act to push the cell face inward which closes a valve arrangement included in the counter-pressure system. By increasing the counter pressure, the face can be forced backward into the rock. The pressure at which the valves open equals the rock pressure. These cells have been used widely in soils and to a limited extent in rock. They are applicable to monitoring stresses in bedded salt.

Cylindrical borehole cells can be used in an uncalibrated or a calibrated mode. For the uncalibrated mode, the physical properties of the rock and the cell must be known. The pressure-volume response of the pump-cell system and the elastic properties of the rock must be known, if changes in cell pressure are to be related to changes in rock stress (Sellers, 1970). For the calibrated mode, the cell is pressure-cycled in calibration cylinders of different elastic properties before placement in a borehole. This cycling yields the complete physical characteristics of the pump-cell system. Then the cell is placed in the borehole and pressure-cycled again, exhibiting the elastic properties of the rock. The resulting information is then used to establish a direct relationship between rock stress and cell stress (Panek, Hornsey and Lappi, 1964).

Pressure changes recorded by the cell monitor only the sum of the changes of the two principal rock stresses acting in the plane normal to the borehole axis. Thus, changes in stress can occur that will not be sensed by the cell, the most serious case occurring where an increase in the maximum principal stress is offset by an equal decrease in the minimum principal stress. All cells should be installed with their fluid pressure preset at a value above that of the maximum principal stress. If the rock stress decreases, the borehole diameter will expand, possibly to such a degree that the cell membrane begins to retard the fluid expansion rather than the rock. In this instance, cell pressures will reflect the elastic nature of the membrane and not of the rock. The sensitivity of a cell decreases with an increase in rock modulus, and increases with an increase in cell stiffness, where stiffness is defined as the pressure/volume ratio of the cell system. For this reason, most cells are made as stiff as possible.

A flat cell grouted into a cylindrical borehole is called a Borehole Pressure Cell (BPC), and is a type of flat fluid cell developed by the U.S. Bureau of Mines (Panek and Stock, 1964). In these cells, only rock stress changes acting normally to the flat face of the cell can be monitored; however, two cells oriented at right angles can monitor the biaxial stress changes acting normal to the borehole axis.

Open hole stress monitoring can be done with overcoring probes such as U.S. Bureau of Mines borehole deformation gage. These probes monitor the deformations in the perimeter of the borehole that occur over time. Any changes in regional rock stress will be reflected by a distortion of the borehole wall. Using the theory of elasticity, one can convert these distortions into rock stress changes; however, the elastic properties of the rock must be known. If rock stresses exceed the failure stress of the rock, then failure will occur around the borehole perimeter, and the open-hole readings will be erroneous.

Evaluation of the accuracy of in-situ stress-change measurement devices is difficult. Many types of gages including cylindrical pressure cells, borehole pressure cells, hard inclusion gages (Irad Gage), flat jacks, Glotzl cells, and photoelastic stress meters have produced data for periods of a year or more after emplacement. In most cases, the consistency of the stress change readings has led investigators to assume the results are reliable to at least ±25 percent -- for example, see Clark (1978). But no detailed effort has been reported to document either gage accuracy or the rock and gage characteristics that affect the gage accuracy.

In rock susceptible to creep (such as salt), the rock tends to close around the cell. If the rock has no yield point with respect to creep, creep will continue until the fluid pressure becomes high enough to resist further deformation. At this point, the fluid cell pressure will equal the average rock pressure. Cells of this type have been used in Canadian potash mines (Mraz, 1978).

C. In-Situ Rock Strength and Elastic Moduli Measurement Techniques

For the design of underground openings for a repository in bedded salt, certain basic properties of the associated rocks must be determined. These properties include the elastic moduli and the failure characteristics of each rock type. Values of these properties obtained from in-situ tests are preferable to those obtained from laboratory sample tests because the in-situ data include the effects of large-scale inhomogeneities. To obtain these in-situ values, the rock must be loaded and, thus, some type of jacking is required.

In a jacking test, the rock is forced to deform under an applied load. The load and the deformation are measured simultaneously, and load-deformation curves are constructed. The elastic moduli are calculated from these curves. If failure strengths are desired, the loads can be applied until rock fracturing occurs.

For critical design features, both radial and axial tunnel jacking have been employed because the results include the effects of gross inhomogeneities such as joints or faults. Therefore, the moduli and strength values are more realistic.

Borehole jacks and dilatometers are less expensive and more flexible than large-scale jacking systems, and many such devices have been developed (see Table 3-1). They can be used in rather long boreholes.

Elastic moduli determined by borehole methods have not always correlated well with moduli developed from large-scale jacking tests. There have, therefore, been reservations about using borehole-developed moduli values for critical design applications (Meyer and McVey, 1974).

In-situ rock strength can also be determined by jacking as indicated in Table 3-1. Borehole jacking can determine the tensile strength of a rock (Goodman, Van, and Heuze, 1972). Plate-bearing tests can yield estimates of rock compressive strength (Wagner and Schumann, 1971). Flat jacks can be used to determine compressive strength by compressing the rock between two parallel jacks. Shear strength can be determined by a torsion test (Sellers, 1974).

For all jacking tests, the determination of elastic moduli depends upon accurately modeling the jack-rock behavior. In most cases, modulus values are determined by idealized models of how the jack loads the rock, and of how the jack and rock behave under that load. Improvements in the model include using numerical techniques as described by Heuze and Salem (1976). These authors reported that rock anisotropy, plate stiffness, and radial cracking in the rock can strongly affect modulus values unless accounted for. In addition, Hustrulid (1976) reports that a curvature mismatch between borehole jack platten and the borehole can cause substantial errors in modulus determinations. Additional research is required to develop reliable techniques for calculating modulus values and for performing tests.

D. In-Situ Displacement Measurement Techniques

Displacements are measured in order to determine rock movements. The analysis of the displacements must take into account both the scale of measurement and the source from which they arise.

In Table 3-1, displacement measurement techniques are divided into three categories:

- Small-scale techniques
- Extensometer techniques
- Surveying techniques.

Small-scale methods include instruments that can measure displacements in the range of micro-inches to perhaps 0.01 inch. Small-scale methods employ measuring instruments with small gage lengths (distances between measuring points). They most often are used to determine rock stress.

Extensometer techniques include instruments that can measure displacements in the range from 0.001 inch to perhaps several feet. Extensometers are characterized by the attachment of rods, tubes, or tensioned wires to measuring points, and then measuring the relative movements. Displacements between points on the rock are transferred to equal displacements on rods, tubes, or wires where measurement is more convenient. Gage lengths range from less than a foot for hand-held gages to hundreds of feet for borehole-installed wire and rod systems. Van Schalkwyk (1976) reports capabilities to measure with an accuracy of $\pm$0.001-inch over a displacement range of 0.5 inch in a 500-foot-long extensometer.

Surveying techniques are used to measure rock deformations greater than 0.01 inch. Normally, they are used where extensometer techniques are not applicable, or in situations where baseline data are needed--such as the total initial distance between two points or the initial elevation of a point. Surveying has been extensively used in monitoring subsidence and settlement above mines and tunnels. Surveying techniques can be used both above ground and underground. In general, all the displacement techniques produce accurate, reliable data if gage installation and monitoring are done properly.

E. <u>In-Situ Tilt Angle Measurement Techniques</u>

Tilt can be measured on a rock surface or in boreholes. Since all changes in the orientation of a flat face or a borehole are caused only by rock deformation, the repeated measurement of tilt angles monitors rock deformations.

Borehole inclinometers are used extensively to monitor soil and rock movements in the plane normal to the borehole axis. (For the case of a vertical borehole, horizontal movements would be monitored.) Tilt measurements made at selected intervals along the length of the borehole are used to calculate the position of the borehole at each measurement depth. Repeated measurements at given time intervals can be used to plot movements of the borehole.

Still in the development stage, the three-dimensional tiltmeter (listed in Table 3-1) promises more accurate depth measurements than are possible with present methods. This instrument will provide the added capability of measuring a borehole's longitudinal extension or contraction as well as its horizontal movement.

The following accuracies are obtainable with carefully installed instruments:

- Photographic Tiltmeters: 1 to 5 minutes of arc depending upon total arc to be measured (Van Schalkwyk, 1976)

- Spirit Levels: ±0.15 degree of arc normally, but ±2 seconds of arc obtainable in specially designed electric units (Sherwood and Curry, 1976)

- Borehole Tiltmeters: ±3 seconds of arc (Van Schalkwyk, 1976; Cornforth, 1973)

  A horizontal displacement of 0.20 inch is detectable over a 100-foot length of vertical borehole using accurate tiltmeter readings and statistical data analysis methods.

F. In-Situ Creep Measurement Techniques

1. Testing - Few in-situ tests are designed specifically to determine rock creep properties. However, both borehole and tunnel jacking tests can be designed to measure rock creep. In both situations, two basic approaches can be taken. In the first, a load would be applied to a borehole wall or a rock face and held constant over time. Any rock deformation would result from creep, the total creep load being the in-situ stresses plus the jack load. A series of load tests would result in different creep rates which can be used to generate creep parameters. Only one instance of a test of this type was found in the literature (Cogan, 1976).

In the second approach, the rock loads would be varied in order to control deformation rates. For example, the walls of an open borehole creep inward, the driving force resulting from the in-situ stresses. This inward movement can be retarded by pressurizing the hole with a fluid. The inward creep rates correspond to specific borehole pressures, and can be used to derive in-situ creep parameters if the stresses are known. Similar approaches could be worked out for borehole jacking, tunnel jacking, flat jacking, and other testing techniques.

2. Monitoring - Experience has shown that creep deformations underground occur at constant rates, and that the monitoring of these rates can be used to analyze rock behavior around openings. The average creep rates of tunnel walls can be used to estimate future deflections of tunnel walls. High closure rates in competent rocks can indicate that the rock is near failure. Spontaneous increases in creep rate indicate changes in stress conditions, or initiation of rock failure. Decreases in creep rate indicate decreases in rock loading or a strengthening of the rock. Changes in the creep rate, such as sudden increases in total deformation, may indicate rock fracturing.

Stress conditions are affected by heat through thermoelastic action and creep parameter alteration. Extensometer and tiltmeter data, recording creep behavior, changing under stress conditions are more difficult to interpret.

Extensometers and tiltmeters have been used to monitor creep deformation vs. time in mines, tunnels, and around other underground openings. These instruments measure total deformational changes that occur with reference to the rock state at the time of (instrument) installation. Each measurement can include elastic, plastic, and creep deformations. However, most rocks are brittle at the stresses found around engineered openings, and it has been difficult to identify plastic deformational components. Elastic deformations are measured only for changes in rock stress brought about by mining or the application of loads to the rock. The result of these stress changes is an initial elastic deformation followed by a change in the creep rate. But for most cases it is very difficult to recognize the elastic deformations. Thus, under normal conditions deformation-time data usually reflect creep behavior.

The above discussion applies to salt strata as well as to other types of rock. Since salt is highly prone to creep, monitoring is easily accomplished. Creep deformation data together with temperature and stress data can be used to monitor repository rock behavior over time--before, during, and after emplacement.

3.3 LABORATORY MEASUREMENT TECHNIQUES

Laboratory stress-strain testing is designed to produce basic rock property data from rock samples collected in the field. Results characterize rock behavior exclusive of on-site geologic inhomogeneities.

Laboratory-determined physical properties of rocks are used to classify the rocks by type, to help establish design criteria for openings, to corroborate in-situ-determined properties, to provide data for mathematical modeling, and to provide a data bank of rock properties for analytical procedures.

Basic data required for evaluation, analysis, and design of a repository in bedded salt are (Duvall, 1976)

- Rock density
- Elastic modulus
- Poisson's ratio
- Uniaxial compressive strength
- Triaxial compressive strength (solid core)
- Triaxial compressive strength (cores with planes of weakness)
- Modulus of rupture
- Tensile strength
- Creep constants.

The laboratory techniques shown in Table 3-1 determine these properties. Variations of these techniques have been used to develop specialized tests. Other tests, independent of these techniques, exist but are not listed (Lama and Vutukuri, 1978). Laboratory testing of creep is included in Appendix B.

3.4 SUMMARY AND CONCLUSIONS

A wide variety of measurement techniques can be used to determine the rock mechanical behavior of a repository in bedded salt. The capabilities exist to measure stress, stress change, strength, mechanical properties, displacements, and tilt-angle changes of in-situ rock. In addition, laboratory testing procedures are available to determine rock properties under extreme conditions of stress, strain, and temperature.

The data collected from these measurement techniques can be used for a variety of purposes, including

- Preliminary evaluation of site rock characteristics, including long-term stability
- Preliminary evaluation of containment capabilities of site rocks
- Preparation of design specifications for rockwork facilities
- Monitoring and assessment of pre-emplacement rock behavior
- Monitoring and assessment of post-emplacement rock behavior
- Monitoring and assessment of post-decommissioning rock behavior.

Rock stress measurements can be made by hydrofracturing, jacking, or overcoring. Hydrofracturing introduces fractures that may act as water flow paths; jacking techniques can be used, but yield only a limited amount of data; overcoring techniques are the most flexible and improved methods are being developed. With the present state-of-the-art, stress determinations in hard rocks can be made with a reasonable degree of accuracy and reliability.

Necessary improvements in overcoring techniques include (1) a probe that can reliably measure the full stress state in a single borehole, (2) a soft-inclusion probe that can make stress determinations in soft and fractured rocks, and (3) techniques that can be used in boreholes over 100 feet deep.

In-situ elastic properties and rock strength can be determined by jacking test, including borehole tests, tunnel jacking tests, and plate bearing tests. It is often difficult to correlate small- and large-scale tests since rock inhomogeneities have a greater effect on tests with longer jacking surfaces. Borehole jacking tests need improvements in equipment design, operating techniques, and data analysis to improve data correlation with large-scale tests. Large-scale tests need redesign to reduce the time and expense of testing.

Stress changes in a repository can be monitored in boreholes with permanently emplaced, hard-inclusion and soft-inclusion stress gages. For the most part, these gages monitor stress changes that occur normal to the borehole axis. All of the many types of available gages record only stress changes relative to the stress induced during emplacement. Both fluid-filled and hard-inclusion gages have been used in salt mines. Improvements in equipment should include the development of hard-inclusion and soft-inclusion gages that would record stress changes both parallel to and normal to the borehole axis. A better understanding of rock creep effects on gage performance is also needed.

Deformation and tilt-angle measurements are reliable and accurate. Present capabilities exist for measuring almost any type of rock deformation. Instruments are available for monitoring most types of deformation behavior that could occur in a salt repository. New developments will streamline gage installation and automate data acquisition and processing.

Existing laboratory techniques can both heat and induce pore-water and confining stresses upon test specimens. Uniaxial and triaxial tests can measure elastic, plastic, creep, and post-failure behavior of salt and associated strata. Testing standardization is limited to uniaxial and triaxial strength tests. For a repository in bedded salt, standard procedures for creep testing and full-scale triaxial testing should be developed.

Schedule

The application of rock mechanics measurement techniques will vary with the stage of repository development. In the early stages, basic data must be obtained to evaluate and plan the underground facilities. As more information is collected about rock properties and in-situ behavior, the emphasis will shift from sampling, testing and general data collection to monitoring and observing rock behavior under actual repository conditions.

Site Selection (Stage A)

During reconnaissance and exploration, rock sampling and testing will be required for the evaluation of the site. Both borehole core samples and grab samples can be collected. Testing will determine rock strength, creep parameters, elastic moduli, failure characteristics, failure parameters, and other data associated with rock stability. These tests should be done on both salt and its associated strata. Laboratory testing will dominate at this stage.

During this stage, exploration shafts and tunnels will be excavated. In-situ rock testing will be used to establish a correlation between laboratory test data and in-situ behavior. Further sampling and laboratory testing can be conducted. The main objective is to generate data that can be used for the design of underground openings and for analyzing repository stress-deformation behavior.

Construction (Stage B)

By the time approval for emplacement has been received, a mass of rock property data will have been collected. At this stage, monitoring will become more important, and will include measurements of rock stresses and deformations over time. These measurements can be used to check design assumptions against actual creep behavior, identify potentially unstable rock areas, and establish a general understanding of repository stress-deformation behavior.

Emplacement (Stage C)

Once waste emplacement begins, heat will start to flow into repository rocks and temperatures will rise. In-situ stress and stress-deformation tests can be performed to determine the effects of heat upon the rocks. In addition, monitoring stations can be installed to observe rock stability in heated areas. Data from these monitoring stations will aid in accessing retrievability of waste.

Decommissioning (Stage D)

Once waste has been sealed in a room, data collection must be accomplished by remote methods since direct access is no longer available. Monitoring the emplacement areas can be done through drillholes. Deformation monitoring can be used to identify roof collapse, pillar failure, slip along rock fracture, subsidence, and other features that can affect containment.

TABLE 3-1

Sheet 1 of 20

ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Stress	IN-SITU MEASUREMENT TECHNIQUES			
	A. In-Situ Stress			
	Borehole Overcoring	To determine in-situ coring stress normal to borehole axis	B, C	Technique measures rock stresses by monitoring stress relaxation inside small borehole after drilling a larger sized hole around it. This is a standard method of determining rock stress. (Agarwal and Boshkov, 1966; Berry and Fairhurst, 1966; Fairhurst, 1968; Roberts, 1968; Hoskins, 1967)
	Biaxial stress determination			Strains on perimeter of borehole are monitored and converted into stress.
	Open-Hole Methods			
	• Borehole Deformation Gage (USA)			Strain gage instrument measures radial distortions in hole during overcore drilling. Distortion is converted into stresses. (Obert, Merrill and Morgan, 1962; Merrill, 1967)
	• Doorstopper Technique (S. Africa)			A strain gage rosette is cemented to the face of an EX (1-1/2" diam.) borehole. As hole is overcored, stress relaxation of face is recorded. (Leeman, 1969)
	• Griswold Gage			Similar to borehole deformation gage. (Royea, 1970)
	• Hawke's Stressmeter (England)			A photoelectric plug is cemented to the end of a borehole and monitored during overcoring. (Hawkes and Moxon, 1965)
	• White Pine LVTD[2/] Gage			(Perrin and Scott, 1964)
	• Four-Component Deformation Cell (USA)			Similar to borehole deformation gage. (Crouch and Fairhurst, 1967)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

2/ Linear voltage differential transducer, also known as linear variable differential transformer.

ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Stress (Cont'd.)	A. In-Situ Stress			
	Borehole Overcoring (Cont'd)			
	Biaxial stress determination (cont'd.)			
	Hard-Inclusion Methods		B, C	Strains that develop in a hard inclusion wedged into borehole are measured and converted into stress.
	• Hast's Stressmeter (Sweden)			A metal stud with an electrical wire coil wound around it is wedged into a borehole. Straining during overcoring is converted into changes in coil inductance. Inductance is converted into stress by calibrating the probe. (Hast, 1958)
	• Borehole Deformation (Belgium)			Uses six (6) LVDTs to monitor borehole surface deformations. (Bonnechere and Cornet, 1977)
	• Talbot Strain Cell (England)			Similar to CSIR cell but strain rosettes are held against borehole wall and not cemented. (Potts, Szeki, and Rowley, 1974; Potts, Dunham, Maconochie and Reid, 1976)
	Soft-Inclusion Method			Hole deforms as if inclusion were not present.
	• Cast Photoelastic Inclusion			A photoelastic, expoxy resin plug is cemented into a borehole and overcored. Fringe lines are measured. (Riley, Goodman and Nolting, 1977)
	Triaxial stress determination			
	Open-Hole Methods			
	• CSIR (Council on Scientific and Industrial Research) Techniques			Strain gages are cemented to hole wall. Strains are monitored as overcoring proceeds and converted into stresses. (Leeman, 1964a, 1964b, 1964c)
	Hard-Inclusion Method			
	• USGS Solid Inclusion (USA)			Strain gage rosettes are cemented to a steel ball. Steel ball is encased in plastic and then cemented into borehole for overcoring. (Nichols, Abel and Lee, 1968; Abel and Lee, 1973)
	• Rigid Inclusion (Poland)			Specially designed rigid cylinder for use in coal mines. (Fileek and Cyrul, 1977)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 3-1

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Stress (Cont'd.)	A. In-Situ Stress			
	Borehole Overcoring (Cont'd)			
	Triaxial stress determination (cont'd.)			
	Soft-Inclusion Methods.			Hole deforms as if inclusion were not present.
	• Soft-Inclusion Gage (Portugal)		B, C	Plastic cylinder containing strain gages is embedded in borehole; strains are monitored during overcoring and converted into stresses. (Rocha, 1966; Rocha and Silverio, 1969)
	• Soft-Inclusion Instrument (Australia)		B, C	Similar to soft-inclusion gage above. (Blackwood, 1977)
	Flat Jack Techniques	Measure rock stress	B, C	A flat jack is installed in a slot cut normally into a rock face. Rock deformations before and after slot cutting are monitored. Then jack is pressurized until initial deformation is reached. Jack pressure at full return equals in-situ stress normal to jack. (Tencelin, 1951; Hoskins, 1966; Ageton, 1967)
	Hydrofracturing	Determine minimum rock stress adjacent to a borehole	Not recommended	Measurement is made of fluid pressure required to fracture rock adjacent to a plugged borehole. Capable of use in deep boreholes. (Hubbert and Willis, 1957; Haimson, 1968; Haimson, 1974; Rogiers, 1975; Haimson, 1977)
In-Situ Stress: Residual Stress	Creep Recovery Measurements	Determine in-situ stress, residual stress, elastic modulus	A, B, C	Instrument orients drill cores upon removal from borehole and monitors strain changes over time. Plots of creep rate vs. time when compared with core laboratory tests yield residual stresses. Not tried on salt. (Voight, 1967; Friedman, 1972)
In-Situ Stress: Rock Supports	Three Basic Types of Instrumentation	Monitor support stresses	B, C	Used to check stability of supports.
	• Load cells			Hydraulic transducers used to measure axial compression or tension. Can monitor rock bolt loads, prop loads and bearing loads.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 3-1

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters		Measurement Techniques	Purpose	Stage[1]	Remarks
In-Situ Stress: Rock Supports (Cont'd.)	A.	In-Situ Stress (Cont'd.)			
		Three Basic Types of Instrumentation (Cont'd.)			
		• Flat jacks			Flat fluid-pressure cells. Can be placed into mass concrete to monitor stress changes.
		• Strain gages			Many types exist. Can be attached to any steel member including rebar in concrete.
In-Situ Rock Stress Changes	B.	In-Situ Stress Change			
		Stress-Measuring/Instruments	Monitor stress changes and creep over time	B, C	All open-hole hard and soft-inclusion borehole probes used for overcoring and modulus determination can be used to monitor borehole closure with time. If rock creeps, closure will represent creep strain effects as well as stress change effects. The best instruments for long-term monitoring are listed in the second column below. (References previously cited).
		• Borehole Deformation Gage (USA)			
		• CSIR Triaxial Cell (S. Africa)			
		• Four-Component Deformation Gage (USA)			Previously described for stress measurements.
		• Cast Photoelastic Inclusion (USA)			
		• Borehole Deformation Cell (Belgium)			
		• Talbot Strain Cell (England)			
		• Soft-Inclusion Gage (Portugal)			
		• Soft-Inclusion Instrument (Australia)			

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Stress Changes (Cont'd.)	B. In-Situ Stress Change (Cont'd.)			
	Hard-Inclusion Gages specially designed for change measurements	Monitor stress changes	B, C	Strains in boreholes are monitored over time and converted to stresses. Mostly used in soft rocks and coal. Are applicable to salt mines.
	• Irad Gage (USA)			Hard inclusion is wedged into borehole. Vibrating wire system senses stress changes on inclusion. (Hawkes and Bailey, 1965)
	• Solid Inclusion Stress Gage (England)			Developed by National Coal Board (England) for use in coal mines. (Wilson, 1961)
	• USGS Solid Inclusion Gage			A strain gage instrumented steel ball encased in epoxy was tested in a mine. Not tried in salt. (Abel and Lee, 1973)
	• Potts's Stressmeter (England)			Initial use of gage was in a salt mine. (Potts, 1957; Potts, 1964)
	• Wilson's Stressmeter			Similar to English Solid-Inclusion Stress Gage. (Wilson, 1961)
	• Photoelastic Plug Technique (England)			Photoelastic disk is set in the hole and distorts as stress is relieved. Stress pattern caused by distortion is monitored. (Roberts, 1968)
	• Salt Plug Gages (West Germany)			There are two types. Type I is a salt-filled steel ring instrumented with strain gages. Type 2 is a strain-gage-instrumented plug of fused salt. (Dreyer, 1977)
	• Other Hard-Inclusion Gages			Many hard-inclusion probes used for stress determination by overcoring, or for elastic modulus determination by borehole jacking have been used to monitor stress changes.
	- CSIR Pressiometer (Australia)			(Worotnicki, Enever and Spathis, 1976)
	- Rigid Inclusion Probe (Poland)			(Fileek and Cyrul, 1977)
	- W. German Gage			Vibrating wire transducer monitors stress changes. (Dreyer, 1977)

[1/] Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 3-1

ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Stress Changes (Cont'd.)	B. In-Situ Stress Changes (Cont'd.)			
	Fluid Cells for stress-change measurements	Monitor stress changes	B, C	All soft-inclusion gages used to this date have been fluid-filled pressure cells.
	• Liquid-filled borehole			Monitor pressure change in fluid in a plugged borehole. Creep of salt will stop when pressure equilibrium is reached. Has been used in salt. (Barr, 1960)
	• Flat Slot Method			A flat cell is cemented into a slot in the rock. This cell is connected to a cylindrical cell that acts as a standard pressure source. A differential pressure transducer is placed between the two cells. Rock pressure causes liquid pressure to increase in a flat cell. By adjusting cylindrical cell pressure rock pressure can be read. Not tried in salt, but applicable. (Swolfs and Brechtel, 1977)
	• Flat Jack Monitoring			A flat hydraulic cell is placed in a slot and pressurized; the resulting stress changes are monitored over time using a transducer or pressure gage. Experience in salt not known. (Curth, 1976; Beneez, Bodoyni, Nagy and Szepesi, 1977)
	• Specialized Pressure Cells			Thin-walled cylindrical cells designed for pressure monitoring over time. Used in Canadian potash mines. (Mraz, 1978)
	- IMC (International Minerals Co.) Cell			
	- Hoskin's Cell			
	- SRC (Stress Redistribution Cell) Omni-Directional Cell			
	- White Pine Hydraulic Cell			(Cummings and Parker, 1964)
	Cylindrical Pressure Cell			(Panek, Hornsey and Lappi, 1964)

[1/] Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Stress Changes (Cont'd.)	B. In-Situ Stress Changes (Cont'd.)			
	Fluid Cells (Cont'd.)			
	• Glotzl Cells		B, C	A flat hydraulic cell is placed into a rock slot, into soil, into concrete in a tunnel liner, or at a tunnel liner-soil/rock interface. A counter pressure system is used to pump cell up during operation. At point where cell volume has returned to original volume, counter-pressure equals rock stress normal to cell. Experience in salt is not known. (Carlson, 1958; Glotzl, 1958; Sauer, Gerhard and Sharma, 1977)
In-Situ Rock Strength and Elastic Moduli: Large Scale	C. In-Situ Strength and Elastic Moduli	To determine:		
	Jacking Tests	Elastic moduli, rock shear strength, rock bearing capacity	B	A plate is jacked against a rock surface and the resulting deformations vs. loads are recorded. Normally, jacking tests are used to determine design parameters for water tunnels, foundations and underground chambers. (ASTM, 1969; Cording, Hendron and Deere, 1971).
	• Prop Jacking in Tunnels	Elastic moduli		Place prop across tunnel or against roof and floor, and jack against two walls. Monitor separation distance vs. jack load. Not reported in salt. (Wallace, Slebir and Anderson, 1968; Benson, Murphy and McCreath, 1969; Kruse, 1969)
	• Pressure Chamber Jacking in Tunnels	Elastic moduli		Line and plug tunnel to prevent leakage. After filling cavity with water, increase water pressure and monitor distortions of tunnel. Not performed in salt. (Talobre, 1961; Dodds, 1966)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Strength and Elastic Moduli: Large Scale (Cont'd.)	C. <u>In-Situ Strength and Elastic Moduli (Cont'd.)</u>			
	Jacking Test (Cont'd.)			
	• Shear Jacking Test	Shear modulus and shear strength	B	Use two jacks, one acting normally upon a block of rock, the other for block shearing. Not reported for salt but applicable. (Serafim and Lopes, 1962; Serafim and Guerreiro, 1966)
	• Radial Jacking	Elastic moduli		Line perimeter of a tunnel with flat cells and support against walls with stiff struts. Then pressurize cells and record radial deformation vs. pressure. Not reported for salt but applicable. (Wallace, Slebir and Anderson, 1968; Misterek, 1969; Wallace, Slebir and Anderson, 1969)
	• Plate Bearing Test	Bearing strength, elastic moduli, compression strength		Jack a stiff plate of standard dimensions against a rock surface. Record load vs. penetration and note where maximum load occurs. Not reported for salt but is applicable. (Jenkins, 1960: Coates and Gyenge, 1965; Wagner and Schumann, 1971)
	• Large Flat Jacks	Elastic moduli		Flat jack cells are fitted into precut slots oriented normal to a rock face. Jacks are pressurized and rock deformations across slot are monitored by tranducers incorporated into the jack cells. (Rocha, 1968; Rocha, 1969)
	• Cable Jacking	Elastic moduli		Cable is anchored into a borehole and used to jack a bearing plate toward the anchor. A two-cable system can be used with jacks, both parallel and transverse to cable anchor. Not used in salt. (Zienkiewicz and Stagg, 1967)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Strength and Elastic Moduli: Large Scale (Cont'd.)	C. In-Situ Strength and Elastic Moduli (Cont'd.)			
	Jacking Tests (Cont'd.)			
	• In-Situ Torsion Test	Elastic shear modulus, shear strength	B	Drill donut-shaped hole normal to rock face. Attach clamping system to core and twist core off virgin rock. Not used in salt. (Sellers, 1974)
	• In-Situ Triaxial Compression Test	Elastic properties, shear strength		Both axial stress and confining stress applied to block of rock under shear loading. Not used in salt. (John, 1961)
	• Pillar Jacking	Failure strength of pillars		A pillar is cut between the roof-pillar contact. Jacks are placed in the cut and the pillar is loaded. Has been used only in coal. (Bieniawski, Denkhaus and Vogler, 1970; Lama, 1970)
	• Pull-Out Test	In-situ rock tensile strength		Pull anchored bolt out of a rock face. Measure force to pull it out. Salt experience not known. (Evans, 1964; Foote, 1964)
In-Situ Rock Strength and Elastic Moduli: Small Scale				
	Borehole Jacking	Elastic rock modulus normal to borehole axis	B, C	A jack expands sides of borehole laterally and the amount of expansion is measured against the applied force. All borehole jacks are applicable to bedded salt.
	• Goodman Jack (USA)			Monitors total expansion between opposite sides of borehole, at points where jack pads contact rock surface. Data reduction requires corrections for: (1) differences in curvature between the jack and hole walls, and (2) the dissimilarity in stiffness between the loading pads and the rock. (Heuze and Goodman, 1970)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 3-1

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Strength and Elastic Moduli: Small Scale (Cont'd.)	C. In-Situ Strength and Elastic Moduli (Cont'd.)			
	Borehole Jacking (Cont'd.)			
	• Modified Goodman Jack (USA)		B, C	Monitors extension strains in borehole wall rock at points to each side of jack pads. (de la Cruz, 1978)
	• CSIR Pressiometer (Australia)			Information lacking Worotnicki, Enevers and Spathis, 1976)
	• Geoextensometer (France)			Information lacking. (Absi and Seguin, 1967; Hast, 1958)
	• Centrex Cell (France)			A split cylindrical sleeve is forced apart by a conical mandrel. (Noel, 1963)
	• Borehole Jack (W. Germany)			A split cylindrical sleeve is forced apart by an advancing screw. (Martini, Durbaum and Giesel, 1964).
	• Borehole Pressure Cell (USA)			Flat jack cast into cement cylinder and placed into a borehole. Has been used in salt. (Panek and Stock, 1964)
	• Talobre's Jack			See Borehole Jack (W. Germany) above. (Talobre, 1961) Limited to shallow holes.
	Borehole Dilatometers	Elastic moduli	B, C	A uniform radial stress is applied to a section of borehole and radial displacements are measured against radial stress. All dilatometers are applicable to bedded salt.
	• Menard Pressuremeter (France)			Designed for soils but applicable to soft rocks. (Menard, 1957 and 1966)
	• Modified Menard Pressuremeter (France)			Modified version of Menard Pressuremeter for applications in hard rocks. Salt experience unknown. (Alas, 1968)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Strength and Elastic Moduli: Small Scale (Cont'd.)	C. In-Situ Strength and Elastic Moduli (Cont'd.)			
	Borehole Dilatometers (Cont'd.)			
	• Cylindrical Pressure Cell (USA)			Copper sheath is jacketed against borehole inner diameter. Fluid volume changes indicate borehole strain. Has been used in salt. (Panek, Hornsey and Lappi, 1964).
	• LNEC (Laboratorio Nacional de Engenharia Civil - Portugal) Dilatometer		B, C	Used for dam design. (Rocha, 1966)
	• Others			References:
	- Pressuremeter (W. Germany)			(Pahl, 1977)
	- Elastometer (Japan)			(Oyo Instrument Company, 1979)
	- Yachiyo Tube Deformeter (Japan)			(Yachiyo Engineering Company, 1979)
	- Geoprobe (USA)			(Testlab Corp., 1967)
	- Rodiometer (Italy)			Information lacking.
	- Unnamed			(Janod and Mermin, 1954)
	- Unnamed			(Kujundic and Stojakovic, 1964)
	- Unnamed			(Comes, 1965)
	- Unnamed			(MacKinley and Anderson, 1975)
	- Unnamed			(Mayer, 1964)
	- Unnamed			(Jaeger and Cook, 1964)
	• CSM (Colorado School of Mines) Dilatometer (USA)			Similar to cylindrical pressure cell but probe is made of plastic. (Hustrulid and Hustrulid, 1973; Patricio and Beus, 1976)
	• Rock Borehole Shear Test (RBST)	To determine rock shear strength, angle of internal friction		Jack forces plates against side of a borehole. A second jack pulls plate along hole axis. Record slip against sides of borehole vs. force. New instrument not tried in salt. (Handy, Pitt, Engle and Klockow, 1976)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Rock Strength and Hardness Tests and Elastic Moduli	C. In-Situ Strength and Elastic Moduli (Cont'd.)			
	Borehole Penetrometers	Determine rock penetrability, elastic modulus	B, C	A small rigid die is forced into borehole wall. (Hult, 1963; Dryselius, 1965; Stears, 1965)
	Schmidt Hammer	Estimate rock hardness		A hard steel piston is rebounded against a rock face. Used to estimate weathering of rock surfaces in hard rocks. (Miller, 1965; ISRM, 1977; Roberts, 1977)
In-Situ Displacement	D. In-Situ Displacement			
	Small-Scale Techniques	Monitor small (μ in. to 0.01 in.) displacements between near points		
	• Carlson Meter			Unit is normally placed in poured concrete to monitor small elastic displacements or displacements across joints in the concrete. It uses elastic wire strain gages. Ends of wire are attached to one section each of two sliding steel cylinders. Not normally used in salt. Could be fixed into boreholes. Also used to measure temperatures. (Carlson, 1958)
	• Vibrating Wire Strain Gages		B, C	Units can be mounted on reinforcing bar in concrete, on concrete itself, on steel members and on rock face. As deformation occurs, it stretches the wire. This changes natural frequency of wire when wire is plucked, and frequency change is calibrated for indicating total displacement. Applicable co bedded salt for measuring rock strains. (Dreyer, 1977; Sinco, 1979)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Displacement (Cont'd)	D. In-Situ Displacement (Cont'd.)			
	Small-Scale Tech. (Cont'd.)			
	• LVDTs, Potentiometers		B, C	Accurate instruments to measure displacements between points. Widely used as measurement elements for gages. Are mounted on extensometers, borehole probes, dilatometers, and other instruments.
	• Mechanical Devices			Depth gages, accurate tapes, micrometer machinist's gages, etc. These are all common measurement tools used by surveyors and machinists.
	• Whitmore Gage			Mechanical gage to measure accurately changes in distance between two studs about 6-10 inches apart.
	Extensometer Techniques	Monitor rock deformation (displacements from 0.001 in. to several ft.)	B, C, D	Permanent measuring points are installed, and distance changes between points are measured with time. All extensometers can be used in bedded salt. (Cording, Hendron and Deere, 1971; Smith and Burland, 1976; ISRM, 1978)
	• Invar Tube Extensometer			Portable instrument. Used to monitor tunnel closure, between spads embedded in tunnel walls, or roof and floor. Consists of two tubes or rods, one sliding in relationship to the other.
	- Reed Extensometer			(Terrametrics, 1979)
	- Distometer (Switzerland)			(Kovari, Amstad and Fritz, 1977)
	- Deformeter (Switzerland)			(Kovari, Amstad and Fritz, 1977)
	- Huggenburger Gage (Switzerland)			(Sinco, 1979)
	• Borehole Rod Extensometer			Rods are anchored at selected points in a borehole and transfer displacements to collar of hole. Measure elongation or shortening between anchor points over time. Used in soil and rock, and in vertical, angled and horizontal boreholes. Holes to 100 ft. and more can be monitored. Many commercial units available. (Sinco, 1979; Terrametrics, 1979)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Displacement (Cont'd.)	D. In-Situ Displacement (Cont'd.)			
	Extensometer Techniques (Cont'd.)			
	• Borehole Wire Extensometer		B, C, D	Same as Borehole Rod Extensometer, but stressed wires are used to transfer displacements. Many commercial units available. (Hedley, 1969; Terrametrics, 1979)
	• Borehole Settlement Probes			Wire extensometers especially designed for vertical holes in soil. (Sinco, 1979)
	• Borehole Induction Coil Extensometer			Borehole casing with induction coils wound around outside perimeter at set locations is installed in borehole. Introduce probe down casing and monitor changes in coil location with respect to hole collar. (Bellier and Debreuille, 1977)
	• Convergence Gages			Similar to Invar tube extensometer. One end of each tube anchored to tunnel wall, roof, or floor. Measure slippage between tubes as anchor points converge or diverge. Gage may be left in place or anchor points can be installed and portable gage used. Automatic recording units are available. Have been used extensively in salt mines. (Terrametrics, 1979)
	Surveying Techniques[2/]			
	• Standard Surveying	Monitor rock deformation (displacements > 0.01 in.)	A, B, C, D	Monitor surface subsidence, monument movements, tunnel wall distortions, etc. Uses accurate levelling and first-order transit runs. (Staley, 1964; Davis, Foote, Kelly, 1966)
	- Level			General surveying and subsidence monitoring.
	- Mine Transit			General surveying, angle determination, and stadia surveys.
	- Theodolite			General surveying, angle determination, stadia surveys, triangulation.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

2/ Surveying Techniques are more fully discussed in Chapter 2 and Table 2-1.

ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Displacement (Cont'd.)	D. In-Situ Displacement (Cont'd.)			
	Surveying Techniques (Cont'd.)		A, B, C, D	
	- Geotheodolite			General surveying, angle determination, stadia surveys, triangulation.
	- Surveyor's Tape			Distance determination.
	- Plumb Lines			Establish vertical reference line.
				All of the above instruments can be used to monitor rock movements in bedded salt.
	• Photogrammetry	Scale measurements from photographs		Accurate stereographic photography taken over time from same location. Comparative analysis of photos allows underground measurements of displacements. (McVey, Lewis and Guidice, 1974)
	• Lasers	Measure offset from light beam		Mainly used for tunnel alignment control. Can be used to measure changes in location of points normal to laser beam. Also can be used to plumb shafts and to check shaft alignment. (Chrzanowski, 1970)
	• Electronic Distance Meters (EDM)	Measure distance		Measure time for electromagnetic wave pulse to travel from instrument to target and back again. Converts time lag to distance.
	- Tellurometer			Infrared wave device. (Commercial instruments)
	- Other			Microwave device. (Commercial Instruments)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
In-Situ Tilt Angle Changes	E. In-Situ Tilt Angle			
	Tiltmeter (Vertical Borehole)	Monitor vertical alignment	B, C, D	Instrument is mounted on a rock surfaces, or in a borehole. If surface or borehole distorts, it will tilt. Normally used for structural members in buildings or on foundation. Applicable to bedded salt. Could monitor underground wall, roof, and floor movements with time. (Sinco, 1979; Telemac, 1979; Terrametrics, 1979)
	Borehole Inclinometer	Measure horizontal movements in boreholes	B, C, D	Accurately measures borehole inclination from vertical plumb along length of borehole. Calculations using tilt and distance yield horizontal displacements of hole. Standard instrument for monitoring rock and soil movements. (Sinco, 1979; Telemac, 1979; Terrametrics, 1979; Terra Technology, 1979)
	Borehole Twist Gage	Measure borehole twist	B, C, D	Measure twist of grooves in inclinometer casing with depth. Applicability to salt is excellent. (Tesch, 1976)
	Horizontal Borehole Inclinometer	Measure horizontal movement in borehole	B, C	Same as borehole inclinometer above but designed for horizontal holes. (Terrametrics, 1979; Sinco, 1979)
	Eastman System	Determine borehole strike and dip	A, B, C	Photographic technique to obtain borehole orientation. Used for determining borehole orientation during drilling. (Eastman, 1979)
	Tropari	Determine borehole strike and dip	A, B, C	Mechanical system used to obtain borehole orientation during drilling. Used mostly in diamond core drilling operations. (Longyear, 1979)
	Three-Dimensional Tiltmeter	Monitor both horizontal and vertical movements in boreholes	B, C, D	Instrument employs pendulum system to measure borehole inclination, and a semiconductor crystal to locate magnets attached to borehole casing for depth measurements. (Smart, Singh and Isaac, 1978).

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
	LABORATORY MEASUREMENT TECHNIQUES	To determine:		
Laboratory Stress-Strain	Laboratory Testing Equipment	Rock physical properties	A, B, C	Round cylinders, cubes and prisms of rock samples are loaded axially and laterally, and resulting deformations are recorded against time. Stress and deformation are recorded at failure. Tests are run on dry rock or rock with pores filled with water. In latter case, pore pressures are monitored. Applicable to salt.
Laboratory Compression				
	Uniaxial Test	Strength of rock samples	A, B, C	Uniaxial Compression - a standard test. Sample is tested only with an axial load. Unconfined compressive strength, stress-strain curve, elastic modulus and Poisson's ratio are obtained. (Wuerker, 1959; Stowe and Ainsworth, 1972; ASTM, 1978l; ISRM, 1979a)
	Triaxial Test		A, B, C	Triaxial Compression - a standard technique. Samples are tested with axial load and various fixed values of confining pressure. Axial loads and corresponding lateral loads are plotted on Mohr diagram to determine cohesion and internal friction angle. (ASTM, 1978m).
	Triaxal Test/ 3-Dimensional		A, B, C	Cubes of rock sample are tested under three different principal stresses. (Serata, Sakurai and Adachi, 1972)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

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ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
Laboratory Shear		To determine:		
		Shear strength		
	Direct Shear Tests		A, B, C	Cylinders or prisms of rock are loaded normally with a set load and then caused to shear along a plane normal to the load. Shear stress vs. shear displacements, shear failure stress, and shear modulus are recorded. Samples can be oriented to fail along bedding planes. Normally used only for soft rocks. (Bernaix, 1969; Protodyakonov, 1969)
	Torsion Test			Rock cylinder is twisted in torsion. (Protodyakonov, 1969)
Laboratory Tension		Tensile strength		
	Uniaxial Tension		A, B, C	Cylinder samples are loaded in tension until samples fail. Monitor load against elongation of sample. Applicable to salt but not a common test. (ASTM, 1978n)
	Brazil Test		A, B, C	Load an axial disk in compression at two opposite locations on perimeter of the disk. Monitor failure load. Common test for competent rock including salt. (Fairhurst, 1964; Hobbs, 1964; Colback, 1966; Jaeger, 1967; Hudson, 1969)
	Modulus of Rigidity Test		A, B, C	Rock beams or cores loaded as beams are bent until tensile failure occurs on tension side. Record beam loads and deflections and calculate tensile stress at failure. Limited use for salt. (Adler, 1970)
Laboratory Fatigue				
	Uniaxial Fatigue Tests	Spectrum of failure stresses as a function of cyclical loading	B, C	Not a common test. Failure is normally by tension. Failure varies with load extremes and fractured state of the sample. (Hardy and Chugh, 1970)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
Laboratory Creep		To determine:		
	Uniaxial/Triaxial Compression	Creep constant	B, C	Creep constants will depend upon the test load. Many tests have been performed on salt. (Lama and Vutukuri, v. III, 1978)
Laboratory Bulk Modulus				
	Consolidation Test	Bulk modulus	A, B, C	Apply a uniform pressure to a rock sample, and its volume contracts. Bulk modulus measures amount of contraction against pressure. (Birch, 1966; Lama and Vutukuri, v. II, 1978)
Laboratory Joint Shear				
	Shear Test	Joint resistance to shear stresses	B, C	Apply shear loads across a joint in a rock sample. Monitor loads and movement to full slippage. Extensive past work on joint shearing. (Lama and Vutukuri, v. IV, 1978)
Laboratory Rock Hardness				
	Indentation Test	Resistance to indentation	B, C	Standard hardness tests and instruments for metals are applicable. Special tests for rocks exist but are not common. Applicable to bedded salt.
	Schmidt Hammer	Rock hardness by rebound	B, C	A spring-loaded steel hammer is impac[illegible] against a rock face. The rebound is measured on a calibrated scale. The higher the rebound, the harder the rock. Can be used in situ and in laboratory (Tarkoy, 1975).
	Shore Scaleiascope	Rock hardness by rebound	B, C	A diamond tipped tool is impacted against a rock surface and height of rebound is measured. Impact is against very small surface area and will yield hardness of individual grains. (Tarkoy, 1975).
Laboratory Specific Gravity		Unit weight of rock samples	A, B, C	
	Balance Scale		A, B, C	Weigh sample dry and then submerged. Determine volume.
	Pycnometer			Crush sample to soil size and use standard pycnometer methods. (Lambe, 1951)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 3-1

ROCK MECHANICS MEASUREMENT TECHNIQUES

Parameters	Measurement Techniques	Purpose	Stage[1/]	Remarks
Laboratory Full-Scale Stress-Strain Properties		To determine:		
	Triaxial Strain-Controlled Testing	Post-failure rock behavior	B, C	Uses triaxial testing apparatus to control axial straining rather than axial load. Sample is taken to failure. At sample failure, load is relaxed automatically as to coincide with strain rate. For low strain, progress to total failure can be monitored against total strain. (Cook and Hojem, 1966; Wawersik, 1968; Rummel and Fairhurst, 1970; Wawersik and Fairhurst, 1970)
Laboratory Miscellaneous Rock Properties				
Swelling Pressure Index	Laboratory Swelling Pressure Cell Tests	Maximum swelling pressure index	B, C	Rocks composed of or containing clay particles tend to absorb water. For some clays, absorption leads to swelling. Swelling pressure can be very high. (ISRM, 1972; ISRM, 1979b).
Slake Durability	Slake Durability Index Test	Rock strength resistance to water saturation	B, C	Samples are dried, weighed, saturated with fluid, dried, weighed etc. Monitor loss of weight. (Franklin and Chandra, 1972; ISRM, 1972; ISRM, 1979b)
Abrasion and Abrasiveness		Rock resistance to abrasion and capacity to resist drilling and cutting	B, C	
	Los Angeles Abrasion Test	Resistance to wear from rubbing and impact		A graded charge of rock aggregate is tumbled in a cylinder for a set number of revolutions at 30 - 33 rpm. Then the charge is removed and a sieve analysis performed. Changes in grading are reported as a percentage of wear. (ASTM, 1969; ISRM, 1978b).
	Tabor Abrasion Test	Determine rock resistance to drill bit abrasive action		As thin disk of NX core is rotated, it is subjected to rubbing action of metal tool. Loss of rock by wear per revolution is measured. Can also determine wear on the tool to evaluate potential for tunnel boring machine use, or possible abrasion of rock surfaces by machinery (Tarkoy, 1975).

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

CHAPTER 4
HYDROLOGIC, HYDROGEOLOGIC AND WATER QUALITY MEASUREMENT TECHNIQUES

4.1 INTRODUCTION

Successful containment of nuclear waste depends in part upon the hydrogeologic regime of the repository site. The migration of water into storage rooms can result in the dissolution of waste and its subsequent transport from a repository into the ground-water system. From the point of entry into the ground-water system, the waste will follow the movement of ground water, and may eventually migrate to the surface. Bedded salt deposits are relatively impermeable; however, even low-permeability formations may permit unacceptable fluid migration.

Measurements of hydrologic, hydrogeologic and water quality parameters are required to assess the transport potential should leakage occur, to establish regulatory guidelines, and to monitor hydrogeologic behavior of a particular repository site. A comprehensive appraisal of a repository site includes

- The extent and hydraulic properties of aquifers and confining beds
- The sources, head distributions, flow rates, and velocities of water in the aquifers in the existing regime and estimates of conditions during construction and emplacement and after a repository is decommissioned
- The chemical and physical properties of water in the aquifers during the existing regime, and factors that may effect changes in these properties.

The extent of aquifers can be defined by the geologic, geophysical, and geodetic measurements described in Chapter 2. The hydraulic properties can be determined by the measurement techniques that are described in Section 4.3 and Table 4-2. The flow system can be defined partly by direct measurement, partly by analysis. The hydraulic head distributions and variations can be measured by methods described in Section 4.3 and Table 4-2. The flow can be determined by an analysis of the hydrologic budget.

The hydrologic budget of a basin is a quantitative expression of the hydrologic cycle applied to a specific area. It may be expressed by the following equation:

> Precipitation + Surface Inflow + Ground-water Inflow + Imported Water = Streamflow + Ground-water Outflow + Exported Water + Evapotranspiration ± Change in Surface Storage ± Change in Ground-water Storage ± Change in Soil Moisture Storage

Evaluating each term of the budget for a heterogeneous basin is impractical. Only those terms that involve inflow, outflow, and storage in the saturated zone affect potential migration from a waste repository. Walton (1970, p. 377) presented the following ground-water budget for a designated area:

> Ground-water Recharge = Ground-water Discharge (to streams) + Ground-water loss through Evapotranspiration + Subsurface Underflow from the Area ± Change in Ground-water Storage

Ground-water recharge includes precipitation that reaches the water table plus ground-water inflow, if any, from adjoining areas. An assessment of ground-water recharge is essential to evaluate the potential mobilization and redistribution of nuclear waste from a repository in contact with ground water. Because the inhomogeneous soil and rocks in most areas preclude estimating with confidence the total recharge from isolated measurements, individual measurements are only a guide to the total ground-water recharge and flow. Models are particularly useful in evaluating possible and probable combinations of hydrologic parameters, particularly if the hydrologic budget is solved under a wide range of stressed and unstressed conditions.

Water quality evaluation involves both the measurement of chemical properties and the evaluation of the effects of those impurities on suitability for use. Water that enters a storage area may mix with and mobilize some of the nuclear waste. From that point, the waste can migrate with the water. The waste materials, however, are also subject to geochemical reactions along the path of flow. The waste material can be absorbed, dispersed, or concentrated, depending upon rock and water chemistry, rock and water temperatures, water pressure, and the manner and rates of flow. Water quality data from in-situ and laboratory tests can be used to determine the effects on waste as it migrates.

Reacti.ns between ground water and rock materials are particularly critical in a bedded salt sequence because of the solubility of sodium chloride .nd other salts. Any changes in flow regime induced during construction and operation of a repository in bedded salt can be expected to be reflected in changes in water quality. Preconstruction measurements of both ground and surface water quality are especially important in order to provide a baseline for monitoring changes during construction and operation of the repository. These methods are listed in Table 4-4. Measurements of the solubility rates of salt are also required. An evaluation of these methods is beyond the scope of this report.

Tables 4-1 through 4-5 list available techniques for measuring the parameters associated with water flow, storage, and quality. In each table, the measurement techniques are organized according to the parameter measured. Each technique is accompanied by remarks explaining pertinent facts about the technique and its application.

4.2 HYDROLOGIC MEASUREMENTS

Measurements of surface-water conditions play a subordinate role in establishing site criteria for nuclear waste repositories. The necessary isolation of the repository imposes constraints that preclude interaction between a waste repository and surface waters. Nevertheless, some measurements of surface-water conditions are required to model the ground-water system and to provide a baseline for predicting and monitoring possible effects of construction activity on the environment.

United States Geological Survey procedures for stream gaging, which have been generally accepted throughout the world, were formalized by Corbett and others (1943). Additional methods and procedures, described in Table 4-1, have been generally accepted as standards; some of these have been evaluated by the World Meteorological Organization (1974). Rantz and others (in press) and Rantz and Herschy and others (in press) describe contemporary stream-gaging practices. These latter compilations presumably will be used as reference standards because of the stature of the promulgating organizations: the U.S. Geological Survey and the World Meteorological Organization.

The recent trend in hydrometry is toward the development of more efficient instruments and the automation of data processing. Also important is the evolution of new concepts such as monitoring networks, hydrological benchmarks, and stream-gaging networks designed to detect hydrologic changes due to natural phenomena and to human activities.

4.3 HYDROGEOLOGIC MEASUREMENTS

A. Ground-Water Levels

Ground-water-level measurements will be required to inventory existing hydrogeologic conditions at the site. Water-level data are important factors in underground construction for the following reasons:

- Water levels are a measure of the total head in a rock formation and therefore of pore pressures in that formation. Water levels in properly constructed wells indicate potential hydrostatic pressures at which water inflow into underground openings can occur if unrestricted flow paths develop.

- Differences in areal and vertical water levels are a measure of hydraulic gradient, which determines the direction of fluid movement and, with hydraulic conductivity, determines the rate of fluid movement.

- Water-level fluctuations are the result of dynamic conditions that indicate stresses imposed on the aquifer. The most common stresses are changes in recharge or discharge due to natural or man-made causes.

Water-level data in conjunction with well testing data can be utilized to study movement of water in the vicinity of the repository area.

Dynamic conditions may be determined by periodic or continuous water-level measurements of the water table or the piezometric surface. The frequency of periodic measurements may extend from less than one minute for a pump test to six months for establishing seasonal variation. The frequency of measurement should be adjusted to the circumstances. In some instances, only a few measurements are possible or expedient to make, but in other instances frequent measurements over a long period of time may be required (U.S. Bureau of Reclamation, 1978). The possibility of error in interpretation decreases as the frequency of measurement and length of record increase. Measurements are made often until the annual regimen is established. The frequency of measurement of some wells may then be reduced. A few carefully selected observation wells may be equipped with continuous recorders. Spacing and frequency should be sufficient to determine changes and the configuration of the water table or piezometric surface. For repository siting, measurements should be initiated prior to construction. Monitoring should continue through construction, emplacement, and after decommissioning to permit comparison of preexisting and post-facility conditions. Such data may be invaluable in the event of claims or suits for damage.

Water-level measurement techniques and equipment have been developed by the U.S. Geological Survey (Shuter & Johnson, 1961; Garber & Koopman, 1968). Some of these methods have been adapted to meet the special requirements of the Nevada Test Site (Garber & Koopman, 1968). The available measurement techniques and the applicability of each technique to monitoring water levels in bedded salt are described in Table 4-2.

B. Measurements of Aquifer Transmitting Capability

Three parameters are commonly used to describe the capability of an aquifer to transmit ground water: permeability, hydraulic conductivity, and transmissivity. Definitions of these and other terms used in this chapter conform to U.S. Geological Survey Standards (Lohman and others, 1972):

- Intrinsic Permeability, k - Intrinsic permeability is a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone and is independent of the nature of the liquid and of the force field causing movement. It is a property of the medium that is dependent upon the shape and size of the pores.

- Hydraulic Conductivity, K - Hydraulic conductivity, K, replaces the term "field coefficient of permeability," P_f, introduced by Meinzer and Wenzel (1942, p. 7), which embodies the inconsistent units gallon, foot, and mile. If a porous medium is isotropic and the fluid is homogeneous, the hydraulic conductivity of the medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow . . . .

  Hydraulic conductivity is dependent primarily on the nature of the pore space, the type of liquid occupying it, and the strength of the gravitational field.

- Transmissivity, T - Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit of width of the aquifer under a unit hydraulic gradient. It replaces the term "coefficient of transmissibility" because by convention it is considered a property of the aquifer, which is transmissive, whereas the contained liquid is transmissible. However, though spoken of as a property of the aquifer, it embodies also the saturated thickness of the aquifer (b) and the properties of the contained liquid. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths.

After a correction has been made for viscosity of the water in the aquifer, the permeability and hydraulic conductivity can be determined either in the laboratory or in the field. The transmissivity and the saturated thickness of the aquifer (b) can be measured only in the field. The hydraulic conductivity (K) can be measured in the laboratory. However, laboratory measurements of transport parameters of bedded salt deposits are inadequate because the structural elements, such as joints and bedding planes that constitute flow paths, are widely spaced. The reliability of field measurements also depends upon geologic conditions such as spacing of structural elements; a large volume of rock must be tested to insure representativeness.

Most aquifer tests are based on the response of well water levels to pumping from or injecting into an aquifer. Water-level changes in the pumped well generally do not indicate the ability of aquifers to transmit water as accurately as water-level changes in observation wells. Measurements in observation wells ordinarily are not affected by well losses or variations in pumping rate and are therefore more reliable than results of tests in which water levels are measured only in pumped wells.

Equilibrium methods based on an analysis by Thiem (1906) or non-equilibrium methods based on an analysis developed by Theis (1935) are applicable. However, short-duration tests (less than a day) can be evaluated using a non-equilibrium method and therefore are commonly employed. Many of the analytic methods are summarized by Stallman (1971) who presents a discussion of the hydrologic conditions and well construction to which each method applies.

Single-hole tests are frequently conducted in which the pumping well is the only observation hole. The common techniques are listed in Table 4-2. Although these tests do not adequately define the capacity of aquifers to transmit water they are valuable for estimating the permeability during exploratory drilling. Constant-head injection tests using packers are generally used. Constant-head and variable-head tests are summarized by Mansur (1971).

Other methods can be used to approximate the capacity of aquifers to transmit water. One method includes estimates of transmissivity based on specific capacity* measurements (Bentall, 1963; Logan, 1964). The reliability of such estimates depends on the quality of the well construction. Another method is to estimate transmissivity from model calibration (Marino and Yeh, 1973; Weeks and others, 1974). The reliability of values determined from this method depends on the reliability of the water budget and the historical water-level record.

Measuring either isotropy or homogeneity of rocks as applied to the capacity for flow is extremely difficult. O'Brien and others (1978) indicated the need for reliable methods in media with similar hydrologic properties to bedded salt. Louis and Pernot (1972) analyzed directional permeability using four peripheral boreholes. However, this method has been used only once, and further use of the method is required to determine its validity. Gringarten and Witherspoon (1972) devised a method of analyzing pumping tests to account for anisotropy introduced by fracture. This method may also be applicable to directional permeability due to bedding planes. Additional methods suggested by O'Brien

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* The specific capacity of a well is "the rate of discharge of water from the well divided by the drawdown of water level within the well. It varies slowly with duration of discharge, which should be stated when known. If the specific capacity is constant except for the time variation, it is roughly proportional to the transmissivity of the acquifer" (Lohman, 1972).

and others (1978) include surface and subsurface methods to identify fractures, and pumping tests to identify boundary effects. Some methods for quantitative measurement of hydraulic properties are currently being demonstrated by Bourke and others (in press).

C. Storage Capacity and Void Space

Many parameters are used to define storage capacity and the volume of space in a rock mass. The most commonly used parameters are dimensionless ratios between the void space, or a property of the void space, and the bulk volume of rock. The values of the parameters are determined in part by empirical measurements, most of which involve draining a rock mass in the laboratory or in the field, and timing the duration of draining.

The commonly used space and storage parameters as defined by Lohman and others (1972) are

- Porosity - The porosity of a rock or soil is its property of containing interstices or voids and may be expressed quantitatively as the ratio of the volume of its interstices to its total volume . . . . With respect to the movement of water only the system of interconnected interstices is significant.

- Effective Porosity - Effective porosity refers to the amount of interconnected pore space available for fluid transmission. . . . Although effective porosity has been used to mean about the same thing as specific yield, such is discouraged. . . .

- Specific Yield - The specific yield of a rock or soil is the ratio of (1) the volume of water which the rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil. The definition implies that gravity drainage is complete.

  In the natural environment, specific yield is generally observed as the change that occurs in the amount of water in storage per unit area of unconfined aquifer as the result of a unit change in head. Such a change in storage is produced by the draining or filling of pore space and is therefore dependent upon particle size, rate of change of the water table, time, and other variables.

Alternative terms, such as void ratio (volume of voids/volume of solids) may be used in expressing the above parameters. Methods for measuring porosity and effective porosity have been described by Meinzer (1923), Stearns (1938), and Pirson (1958). Porosity can be determined approximately by measuring a property of the fluid that fills the void space. For example, geophysical methods such as neutron logs, density logs, sonic logs and electric logs are used to estimate porosity (Telford and others, 1976). The application is described in Appendix A.

- <u>Storage Coefficient</u> - *The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.*

  In a confined water body the water derived from storage with decline in head comes from expansion of the water and compression of the aquifer; similarly, water added to storage with a rise in head is accommodated partly by compression of the water and partly by expansion of the aquifer. In an unconfined aquifer, the amount of water derived from or added to the aquifer by these processes generally is negligible compared to that involved in gravity drainage or filling of pores; hence, in an unconfined aquifer the storage coefficient is virtually equal to the specific yield.

Values of storage coefficients are determined by transient-state pumping tests. Kruseman and de Ritter (1970) summarize the methods to evaluate storage coefficient. Other terms such as specific storage* also define properties of the storage of the aquifer. Such properties cannot be measured in the laboratory or directly in the field without draining the entire aquifer.

Several of the storage parameters are pertinent to the evaluation of waste repository sites in bedded salt. The significant parameters are effective porosity and storage coefficient. Effective porosity, with hydraulic conductivity and hydraulic gradient, is used to determine the

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* The volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

fluid velocity, and with density and distribution coefficient,* K_d, the significant surface-area-dependent distribution coefficient. The storage coefficient affects flow rates during transient flow.

Although effective porosity of granular media can be measured with reasonable reliability, the measurement of effective porosity of rocks at a bedded salt site is extremely difficult because the void space is predominantly represented by fractures. An extremely large volume of rock must be tested to reduce sampling errors. O'Brien and others (1978) concluded that no effective means now exists for directly measuring either total or effective porosity in fractured rock. The use of tracers is the most effective indirect method, but the method involves many assumptions (O'Brien and others, 1978). Snow (1968) estimated the porosity of fractured rocks from permeability tests on single fractures; however, he indicated that the results are conservative. In the future, better estimates may be obtained from model studies, with improved methods of defining fracture continuity (O'Brien and others, 1978).

The storage coefficient for bedded salt terranes is best evaluated using pumping tests in which the results are obtained by measuring water levels in observation holes. This method, which is described by Wenzel (1942), appears to be the only reliable method for testing a large volume of rock. (A large volume must be tested in rocks with fracture permeability such as salt deposits.) A comprehensive discussion of methods of analyzing and evaluating pumping tests is presented by Kruseman and de Ridder (1970). If the water level is to be lowered below the level of the confining bed, the specific yield as determined in the laboratory will have to be used. Laboratory methods yield a good estimate of storage coefficient in unconfined aquifers with moderate to high

* Distribution coefficient is a measure of the distribution of an ion species between the water and the sorbing medium. A high K_d indicates a strong tendency for sorption.

permeability. Therefore, laboratory methods described by Johnson (1967) may be used to estimate the storage coefficient of some unconfined aquifers above bedded salt deposits but not to estimate the storage coefficient of the bedded salt deposits.

D. Hydrogeologic Measurement Problems Associated with Bedded Salt

Many rock strata associated with bedded salt formations are characterized by extremely low intrinsic permeabilities on the order of 10^{-13} cm^2 and less (Gloyna and Reynolds, 1961). Permeabilities as low as these permit only slow water movements under the normal ground-water gradients. Permeabilities in salt and shale generally are so low that the rocks are considered impermeable. However, if these rocks are fractured or cut by joints, faults, or other systems of rock cracking, significant fluid flow through these fissures is possible.

Fluid flow through fractures is highly dependent upon the type of fracture, the fracture distribution, the degree of interconnection, the rock stress, the fluid pressure, the condition of fracture surfaces, and other factors. The porosities and permeabilities of fractured rocks thus depend strongly upon the geometry of fracturing in a rock mass.

The state of development of field techniques for measuring permeabilities, conductivities, and other properties of fractured rocks is not well developed. Techniques for measuring these rock properties were developed for investigations of ground-water supply and of seepage losses. The differences between two low values of a rock's conducting capacity is of little concern in such studies. However, several factors have created interest in more precise methods of determining permeability differences in nearly impermeable rocks. These differences are particularly important in regional and basin ground-water modelling and in questions involving migration of potential contaminants. Techniques developed for soil drainage and petroleum engineering have been adapted to determine quantitatively values of low permeability. Bredehoeft

(1965) suggested adaptation of oil field techniques which have been described by Van Poolen (1960). Many techniques described by Mathews and Russell (1967) and Earlougher (1977) have been adapted to deep ground-water studies. Cooper and others (1967) have adapted analytic methods used in oil fields to determine transmitting capacities using deep ground-water test wells. A similar method has been applied by Bredehoeft and Papadoupulos (in press) to low-permeability rocks at depth where prediction of radionuclide migration is required. The method has been used in many environments, including fractured crystalline rocks below the Atlantic Coastal Plain sediments by Marine (1967) and in volcanic rocks in the Basin and Range Province by Dinwiddie (1968).

Types of permeability tests that are applicable to nearby impermeable rock masses have been evaluated by Wilson and others (1979). These methods, particularly those described by Wang and others (1977), may be adapted to bedded salt. The most promising methods involve measuring effects of flow over long distances in order to average local variations common in bedded salt deposits. Experiments are currently being made by Bourke and others (1979) to compare and to verify the applicability of existing methods.

Progress is needed in defining and characterizing fracture systems, in developing reliable measurement techniques to determine fluid flow and fracture permeabilities, and in perfecting measurement techniques designed to monitor changes in flow or permeability caused by rock temperature and stress changes. Improved techniques should be applicable in holes drilled from underground stations as well as in surface-drilled holes.

At present, techniques used to measure in-situ fracture properties can be grouped into three general categories (Witherspoon, 1977):

- Borehole Packer Tests
- Tracer Tests
- In-Situ Fracture Analysis

A variety of measurement techniques exist and have been used for each category, but difficulties have been encountered in data interpretation.

Various packer tests can be conducted in rock, in water-filled vertical boreholes, or in dry angled holes drilled from underground stations. If a selected length of borehole is sealed by fluid-tight packers at two ends, then the isolated section can be subjected to an increase or to a decrease in pressure. For pumping tests in aquifers, the pressure is reduced because the fluid head is reduced. Fluid will then flow toward the isolated section and flow rates can be monitored. In a hole in fractured rock of very low permeability, or in dry rock, pumping is not possible. In these cases, fluid injection tests are performed.

The fluid injection test consists of pressurizing the air or water in a packed section of borehole and monitoring the change in pressure over time. The pressure or the rate of injection can be kept constant. Normally, though, an equalizing injection pressure eventually develops for any rate of injection inflow. Plots of these equalizing pressures vs. inflow usually show the rate of inflow increasing as the pressure increases.

Variations of the borehole packer test can be tried. Various arrangements of packers can be placed in a borehole to measure flow along the hole axis from one isolated section to another. Two holes can be used and cross-hole flow from one to the other can be measured. Guarded packer tests might be used in which the rock adjacent to the isolated section is prepressurized by radial stresses designed to close rock fractures around the borehole.

Results of packer injection tests are difficult to interpret. To this date, only order-of-magnitude values for permeability have been obtained (Banks, 1972; Maini and Norishad, 1972; DiBiagio and Myrvoll, 1973) because (1) rock fracturing is naturally variable, (2) injection pressures stress the rock, thereby opening fractures and changing the permeability, and (3) problems occur with leaky packers. In addition, there has not been enough careful research work to identify completely the sources of variability.

Pulse injection tests could also be made in which a high fluid pressure is suddenly applied to an isolated section of borehole. The resulting fluid flow or pressure change in that borehole--and possibly in surrounding boreholes--could be monitored (Witherspoon, 1977). Tests of this type have not yet been applied.

Tracer tests are performed by injecting a quantity of trace element into a borehole and observing the arrival of the element in a second borehole. The time of arrival for specific trace-element concentrations are monitored over time. The results can be used to calculate permeability and dispersion coefficients. Additional research is required to develop trace-element techniques with packer tests in fractured rock (Witherspoon, 1977).

Fractures can be analyzed in boreholes by means of TV logging, impression packers, and geophysical logging techniques including acoustic, electrical and magnetic methods. Progress is being made in this area, but more work is required to increase confidence in the data obtained. A greater degree of confidence is needed to make judgments about rock fracture permeability under a variety of conditions. New techniques are needed to observe fracture behavior on borehole walls in response to stress, temperature, and pore-pressure changes; their development is anticipated.

Regional and directional variations in hydraulic properties of nearly impermeable rocks are currently being studied; the results will be published by Neuman (in press).

4.4 WATER QUALITY MEASUREMENT

Monitoring the water environment is achieved by measuring the individual parameters of water quality at the surface and in the unsaturated and saturated zones below the surface or by collecting samples for field or laboratory analysis. Individual constituents dissolved in ground water may migrate with the water. The concentrations of individual constituents in water and rock as well as the rates and quantities of flow over long time periods affect migration of chemical, biologic and radiochemical constituents in the hydrologic system.

In accordance with the requirements of the Federal Water Pollution Control Act (Public Law 92-500) and the Safe Drinking Water Act (Public L w 93-523), the Environmental Protection Agency is authorized to make joint investigations with other Federal agencies, state and interstate agencies, municipalities and industries to prepare or develop a comprehensive program for preventing or reducing the pollution of surface and underground waters (Todd and others, 1976). These objectives are achieved by implementing a monitoring program, with continuing measurements and observations to identify migration of water pollutants and to measure the deviation in water quality from the standards on a regional basis.

Water-quality data acquisition involves in-situ sampling procedures with subsequent analyses for the physical, chemical, and biological constituents in the water. To be truly representative, the integrity of the sample must be maintained from the time of collection to the time of analysis. Lists of sample preservation techniques are presented by Ballinger and others (1974) and Everett and others (1976) to prevent or retard chemical and biological changes in a sample after it is removed from the source. The sampler should be made of non-reactive and absorbent material. In situ samples can be collected at the land surface, the vadose zone, and the saturated zone. Table 4-3 lists the sampling techniques for surface water and for subsurface water in the saturated and unsaturated regimes. Care should be taken during sampling to prevent interference with the flow condition at the sampling point.

The major constituents of water related to water pollution may be classified into physical, chemical, and biological components. The common chemical and physical components that require analyses are listed in Tables 4-4 and 4-5 respectively. The lists in the tables represent the minimum requirements for identifying water pollution problems during a monitoring program.

The inorganic and organic chemical parameters are generally of primary concern in virtually all wastes. Three of the chemical parameters--dissolved oxygen, pH, and oxidation-reduction potential--listed in Table 4-4 should be measured in situ by means of electronic probes (Lytle and others, 1979). The remaining parameters involve laboratory analyses. Radiological parameters are included in Table 4-4. Radiological parameters are generally of concern only in some industrial and mining wastes. Radioactive elements generally are measured in the submicrogram range and therefore may be affected by any background or residual material in the sample container. A radionuclide may also become adsorbed on the surface of suspended particles or on the container material (Everett and others, 1976; Todd and others, 1976). Physical parameters, such as temperature and density, are of concern. Water temperature can be raised by heat generated from radioactive material even if radiochemical constituents are contained. Temperature affects the water density and viscosity, thereby influencing the rate and vertical direction of flow.

Bacteria such as the coliform group, pathogenic microorganisms, and enteric viruses are of primary concern in municipal, animal waste, and septic tank effluent. Coliform organisms, although harmless, have been used as indicators of the presence of pathogenic bacteria, and fecal streptococci are being used increasingly as indicators of significant contamination of water. The coliform count in water can be determined using the membrane filter method (APHA, 1975; ASTM, 1978).

Biological parameters related to water quality are chorophyll-a concentration, carbon fixation rate, phytoplankton, zooplankton, benthic fauna, fish, and macrophytes (Lytle and others, 1979). Measurement techniques for these biological parameters are given by the American Public Health Association (1971), Cairns and Dickson (1973), Edmonson and Winberg (1971), U.S. Federal Interagency Work Group on Designation of Standards for Water Data Acquisition (1972), Slack and others, (1973), Vollenweider (1974), Weber (1973), and Welch (1948).

Meteorological factors may affect the water quality through induced chemical changes and biological productivity in the flow systems, particularly in surface water. The major meteorological parameters that need to be considered are air temperature, wind velocity and direction, relative humidity, precipitation, dew point temperature, evaporation, barometric pressure, radiation, cloud cover and motion. Detailed descriptions of the measurement techniques and instruments involved are given by Middleton and Spilhaus (1953), Sellers (1965), and Stans and others (1970).

4.5 SUMMARY AND CONCLUSIONS

An assessment of the hydrologic regime in the vicinity of nuclear waste repositories is required to determine in advance the possibility of the migration of radionuclides that may not be containe within the repository. The permeability of the rocks at bedded salt deposits is extremely low, so that migration will be determined primarily by the fractures. Therefore, the program to measure hydraulic properties of bedded salt will, in large part, be dictated by the nature and extent of fracturing.

Currently, best method for evaluating the average hydraulic properties of large volumes of fractured rock is to model an entire ground-water basin or any large area for which boundary conditions can be defined. Such a model requires hydrologic data that are based on surface-water as well as ground-water measurements. The chemical and physical properties of the water and rocks also must be determined to evaluate the effect of possible chemical reactions.

Recent research has provided methods for measuring the hydraulic properties of relatively small volumes of rock. These methods are based on techniques developed in both ground-water and petroleum industries. Recent developments notwithstanding, additional research is required to develop new methods and verify the application of new methods to bedded salt.

The dynamics of the hydrologic conditions mandate that the measurement program be initiated as early as possible in repository development in order to define the regime. These measurements will not only provide data for model constructions but will also establish a baseline for continuous monitoring to verify the predictions.

TABLE 4-1

Sheet 1 of 4

HYDROLOGIC MEASUREMENT TECHNIQUES[1/]

Streamflow Parameters	Measurement Techniques	Remarks
Discharge	Weirs	Most efficient where a drop of about 0.5 ft. or more occurs in canal, lateral or ditch. (Grover and Harrington, 1966; United States Bureau of Reclamation, 1967)
	• Standard contracted rectangular weir	Thickness of crest should be between 0.03 and 0.08 in. Distance of the crest from bottom of approach channel should not be less than twice the water height of the above the crest and in no case less than 1 ft. Measurement of head on weir should be taken as the difference in elevation between the crest and the water surface at a point upstream from one weir a distance of four times the maximum head on the crest. Head should be corrected if velocity of approach is high. (Hulsing, 1967; U.S. Bur. Reclamation, 1967)
	• Standard suppressed rectangular weir	Conditions for accuracy of measurement are identical with those of standard contracted rectangular weir (SCRW). Proper aeration beneath nappe at the crest is required. (U.S. Bur. Reclamation, 1967)
	• Standard Cipolletti (Trapezoidal)	Conditions for accuracy are same as those of SCRW. Should not be used for heads less than about 0.2 ft nor greater than one-half the crest length. (U.S. Bur. Reclamation, 1967)
	• Standard 90° V-notch weir	Conditions for accuracy as in SCRW apply. More accurate flow measuring device for small discharge than the preceding types. It is the best type for measuring discharges less than 1 second-foot and is as accurate as the other types for flows from 1 to 10 second-feet. (Hulsing, 1967)
	Parshall flume	Can operate with relatively small head loss in cases when there is insufficient fall for a weir. Relatively insensitive to velocity of approach. Ability to withstand relatively high degree of submergence without affecting the flow rate. Its velocity of flow is sufficiently high to essentially eliminate sediment deposition which would otherwise reduce measurement accuracy. Operates over a wide range of flow rates from 0.01 to 3,000 second-feet. However, its construction requires accurate workmanship, usually more expensive than weirs or submerged orifices and cannot be used in close-coupled combination structures consisting of turnout, control, and measuring devices. Desirable where flow depth is too shallow for current meters and available drop is small. (Boyer, 1964; Corbett, 1962; U.S. Bur. Reclamation, 1967)

1/ Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

TABLE 4-1

HYDROLOGIC MEASUREMENT TECHNIQUES[1/]

Streamflow Parameters	Measurement Techniques	Remarks
Discharge (Continued)		
	Submerged orifice	Is used when there is insufficient fall for a weir and where a Parshall flume is not cost-justified. More susceptible to interference from weeds, trash and sediment that could prevent accurate measurements. The distance from the edges to the bounding surfaces of the channel should be greater than twice the least dimension of the orifice. Cross-sectional area of water prism 20 to 30 ft upstream from the orifice should be at least 8 times the cross-sectional area of the orifice. (Corbett, 1962; Simon, 1976; U.S. Bur. Reclamation, 1967)
	Salt-dilution method	Measures discharge directly without area and distance measurements. For turbulent streams of moderate or small size. Cost depends on dosage required and chemical method for analysis. (Corbett, 1962; U.S. Bur. Reclamation, 1967)
	Color-dilution method	Uses nontoxic dyes that do not deposit on flow surfaces, sediments or weeds. Cost depends on dosage of dye. Choice of dyes depends on physical, chemical and biological effects on them. (Carter and Davidson, 1968; Wilson, 1968)
	Radioisotope method	Dilution method using radioactive tracer. Limited in use because of potential threat to public health. (U.S. Bur. Reclamation, 1967)
	Slope-area method	Requires good estimates of roughness factor and hydraulic radius of the flow cross section. Reach under study should be straight and uniform with no movement or deposition of debris. (Corbett, 1962; Dalrymple and Benson, 1967; Grover and Harrington, 1966)
	Weir stick	Measures discharge of rectangular suppressed weirs over range of about one second-foot to several thousand second-feet. Gage indicates discharge per unit length of weir and also specific head. (U.S. Bur. Reclamation, 1967)
Velocity	Current meters	Preferred over other means of water measurement when large flows are measured and available drop is small. (Boyer, 1964; Corbett, 1962; Grover and Harrington, 1966; Knox, 1956)

[1/] Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stage

TABLE 4-1

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HYDROLOGIC MEASUREMENT TECHNIQUES[1/]

Streamflow Parameters	Measurement Techniques	Remarks
Velocity (Cont'd.)		
	• Price meter	Vertical axis bucket type equipped with air pocket to prevent accumulation of silt in the pivot bearing. (Corbett, 1962; Buchanan and Somers, 1969)
	• Pygmy meter	Smaller version of Price meter; especially designed for use in shallow streams, also in large canals with low flow velocity. Limited to velocities up to 4 feet per second. (Corbett, 1962; U.S. Bur. Reclamation, 1967)
	• Propeller meter	Less sensitive than Price meter to velocity components not parallel to direction of flow (Simon, 1976; U.S. Bur. Reclamation, 1967)
	• Electromagnetic flowmeter	Measures two velocity components within range of zero to 10 ft/sec; equipped with visual display. (Boyer, 1964; Simon, 1976)
	• Optical current meter	Used for quite high velocity flows and for flows carrying debris and heavy sediment. No part of the meter is immersed during operation. Measures only the surface velocity of stream rather than average or integrated velocity. (U.S. Bur. Reclamation, 1967)
	Float	Measures velocity at or close to surface. Floats may be diverted by wind, surface disturbances and cross-currents. Accuracy in measurement may be affected by appreciable changes in stream depth along the test reach and the preciseness of coefficient used to compute discharge. (Boyer, 1964; U.S. Bur. Reclamation, 1967)
	Pitot tube	Measures relatively high velocities in canals, at dr[illegible] [illegible]utes and overflow crest. (Boyer, 1964; Simon, 1976)
	Salt-velocity method	Used in open channels; more generally used in closed conduits. Relatively expensive electrical equipment required. (Corbett, 1962; Grover and Harrington, 1966)
	Color-velocity method	Difficult to detect center of mass of dye. Uncertainty that observed dye velocity represents mean velocity of stream or just surface velocity. (U.S. Bur. Reclamation, 1967)
	Acoustic flowmeter	Accuracy of system depends upon positioning the transducers at the proper heights or depths to obtain true average velocity in the channel. (Boyer, 1964; U.S. Bur. Reclamation, 1967)
	Deflection meter	For midrange velocity measurements. Deflection error may be caused by wind on exposed part of meter. Within 2% accuracy under ideal conditions. (U.S. Bur. Reclamation, 1967)

1/ Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

TABLE 4-1
Sheet 4 of 4

HYDROLOGIC MEASUREMENT TECHNIQUES[1/]

Streamflow Parameters	Measurement Techniques	Remarks
Velocity and depth	Sonic sounder	An assembly of a depth recorder, operating by acoustic reflection, and a Price current meter. Permits measurements without lowering the assembly to the stream bottom; particularly suitable in great depths where debris is a frequent menace to the equipment. (Grover and Harrington, 1966)
Velocity, direction and depth	Velocity-Azimuth-Depth Assembly (VADA)	A combination of a sonic sounder with a remote-indicating compass and a Price current meter. (Buchanan and Somers, 1969; Grover and Harrington, 1966)
Stage	Surface follower	Record continuously. (Grover and Harrington, 1966)
	Ultrasonic device	Equipped with echograph that plot results of continuous measurements across the stream. (Simon, 1976)
	Resistant gage	Measured voltage is linearly proportional to the depth of immersion. (Simon, 1976)
	Water-Level Gages	
	• Staff gage	Non-recording, either vertical or inclined; liable to damage by floating ice, logs and debris. (Boyer, 1964; Grover and Harrington, 1966)
	• Chain gage	Non-recording with horizontal scale. Wind action may introduce error by blowing the weight to one side. Disadvantage of possible fluctuation in height of the structure to which it is attached. (Grover and Harrington, 1966)
	• Wire weight gage	Modification of chain gage with graduated reel or counter. (Boyer, 1964)
	• Float	Usually placed in stilling well to eliminate movements caused by surface waves. May have graphic recorder to produce continuous record of water stages. (U.S. Bur. Reclamation, 1967)
	• Bubble gage	May be equipped with water-stage recorder. (Buchanan and Somers, 1968)
	• Digital recorder	Float and counterweight device with electrically operated paper-tape punch. Most practical for field use where temperature and moisture are widely variable. Electronic translators are used to convert tape records into input for digital computers. (Buchanan and Somers, 1968; U.S. Bur. Reclamation, 1967)
	• Stilling well	Equipped with intake pipes, float and recorder. Structure is well anchored and intake pipes are sized to prevent oscillations of the float by wave action within the well. (Buchanan and Somers, 1968; Corbett, 1962)

1/ Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

TABLE 4-2

HYDROGEOLOGIC MEASUREMENT TECHNIQUE

Parameter	Measurement Techniques	Purpose	Stage[1/]	Remarks
Water Level	Steel Tape	Measure water depth	A - D	A tape reel 1000 to 2000 feet long, mounted on a motor drive provided with braking mechanism. A spring balance attached to the well head enables the operator to maintain tape revision within desired limits during reeling in. Stretch and temperature connections are made. Repeatable to within 0.1 foot at depths of over 1700 feet. (Garber & Koopman, 1968)
	Electric Cable	Measure water depth	A - D	A single-conductor armored cable, winch, and depth indicator are housed in one unit. Different design of water-level sensing probes: self-potential, conductivity, capacitance, inductance, and magnetic types are available. Direct reading to 0.2 foot, and to 0.01 foot by measurement between marks. (Garber & Koopman, 1968)
	Air Line	Measure water depth	A - D	A simple and quick means of measuring water level, especially applicable in pumped wells where more precise methods do not work because of turbulence. A compressed air source and pressure gag., preferably calibrated in feet of water, are required. Depths are read to within 0.25 to 0.5 foot. (Garber & Koopman, 1968)
	Water-Level Recorders	Record water-level fluctuations	A - D	These devices are subdivided into those utilizing water-level sensing probes and those using pressure sensing devices. The latter kind has the advantage of being able to be used in packed or sealed-off zones. (Garber & Koopman, 1968)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 4-2

Sheet 2 of 8

HYDROGEOLOGIC MEASUREMENT TECHNIQUE

Parameter	Measurement Techniques	Purpose	Stage[1/]	Remarks
Water Level (Continued)	Water-Level Recorders (Cont'd.)			
	• Surface Recording Device			The recording mechanism is located on the ground and the water-level fluctuation is transmitted by a cable attached to a sensor to be translated to chart rotation. When a transducer is used, it is anchored to the casing below the water level and responds to rapid changes in pressure.
	• Downhole Recording Device			The unit is small and completely self-contained. Typically, it consists of a pressure sensing element attached to a recording stylus. Originally developed by petroleum engineers, it has potential use for aquifer testing. Clock speed can be adjusted to provide up to 72 hours of continuous recording.
	• Mechanical Recorders	Continuously record water level	A - D	A small-diameter float or probe is attached to a cable strung over a pulley connected to the recording device, and thence to a motor-driven reel. Change in water level causes the sensor to activate the motor causing the reel to release or retrieve the cable and thus follow the new water level. The resulting movement is recorded on the drum. (Shuter and Johnson, 1961)
	- Drescher Float-Gage Attachment			The float movement causes the balance arm and the attached mercury switch to tilt, closing the appropriate electrical switch (Rate of response: 1 ft/min).

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 4-2

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HYDROGEOLOGIC MEASUREMENT TECHNIQUE

Parameter	Measurement Techniques	Purpose	Stage[1/]	Remarks
Water Level (Cont'd.)	• Mechanical Recorders (Cont'd.)			
	- Cradle-Gage Attachment			The recorder and the control mechanism are balanced on knife edges attached to a base. Electrical contacts mounted on each side close as the chassis tilts, because of the movement of the float, and thus operate the motor-driven reel (Rate of response: 3 ft/min).
	- Ferret-Gage Attachment			The probe contains a single-pole, double-flow-throw, center-off switch with attached swinging bar magnet. A small float mounted with a U-shaped magnet is used to actuate the magnetic switch (Rate of response: 2 ft/min).
	• Keck Immersion Element			A weighted probe is suspended in the well by an electric cable that passes over the recorder pulley, and is attached to the reel. An encased pressure sensitive switch actuates the reel motor.
	• Criner Gage Attachment			A water-level-sensing probe is attached to a cable that passes the recorder pulley to a powered reel. Inside the probe a small float is linked to a mercury switch which closes the circuit to drive the reel.
	• Electronic Pressure Transducer Devices	Measure head at pre-set depths	A - D	A pressure transducer installed below the lowest water level expected can be used to determine the changes in hydrostatic head above the transducer. The electrical output, after processing through modulator, demodulator, and amplifier, can be used to drive the recorder. Various designs of pressure transducers are marketed (has future potential, but present cost of installation is high).

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 4-2

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HYDROGEOLOGIC MEASUREMENT TECHNIQUE

Parameter	Measurement Techniques	Purpose	Stage[1/]	Remarks
Flow Parameters: hydraulic conductivity, transmissivity		Determine fluid migration rate		
	Laboratory Methods			
	• Constant Head Permeameter		A - D	Percolate water through sample under constant pressure. Measure pressure and flow rate. Sample not likely to be representative of in-situ rock. (Wenzel 1942; Gloyna and Reynolds, 1961; Morris and Johnson 1967)
	• Transient Flow Apparatus		A - D	Accurate for low-permeability materials (Lin, 1978). Sample not representative of permeability of fractured rocks.
	Field Methods			
	• Constant Head Injection Tests (Water Pressure Tests)		A - D	Field test using one well. Limited area tested; low confidence in extrapolation. Low to moderate reliability. (Mansur, 1971; Ziegler, 1976)
	- Open-End Tests			(USBR, 1974, p. 573-576)
	- Packer Tests			(USBR, 1974, p. 576-578)
	- Lugeon Test			(Hoek and Londe, 1974)
	- Well Permeameter Tests			(USBR, 1974, p. 578-593)
	• Variable Head Injection Tests		A - D	Field test using one well. Limited area tested; low confidence in extrapolation. Low to moderate reliability (Mansur, 1971). Improved reliability in recently tested techniques by Bredehoeft and Papadoupulos (in press), Wang and others (1977). Widely used in petroleum engineering (Matthews and Russell, 1976; Earlougher, 1976). Methods need to be refined and tested for application to ground water.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 4-2

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HYDROGEOLOGIC MEASUREMENT TECHNIQUE

Parameter	Measurement Techniques	Purpose	Stage[1/]	Remarks
Flow Parameters (Cont'd.)	Field Methods (Cont'd.)			
	• Step Drawdown Test		A - D	Field test using one well. Analysis may be questionable (Mogg, 1969). State-of-the-art limited to formations much more permeable than bedded salt. (Rorabaugh, 1953; Lennox, 1966)
	• Slug Injection Tests		A - D	Field test using open well, limited area tested with low confidence in extrapolation. Low to moderate reliability. (Ferris and Knowles, 1963; Papadoupulos and others, 1976)
	• Bailer Tests		A - D	Field tests using one well. Limited area tested with low confidence in extrapolation. Low reliability. (Skibitzke, 1963)
	• Specific Capacity		A - D	Field test using one well. Approximate method restricted to permeable aquifers. (Bentall, 1963, p. 331-338; Logan, 1964)
	• Pumping Test with Observation Holes		A - D	Field test using multiple wells. State-of-the-art limited to formations much more permeable than bedded salt. (Wenzel, 1942; Bruin and Hudson, 1955; Ferris and others, 1962; Walton, 1962; Lohman, 1972)
	Response of Wells to Natural Phenomena		A - D	Field test using observation wells. Water-level response to cyclic phenomena. Not expected to be useful for deep aquifers. (Bentall, 1963, p. 305-330)
	Model Calibration		A - D	Reliability limited by accuracy of measurements or estimates of ground-water system parameters. (Marino and Yeh, 1973; Weeks and others, 1974)
	Leaky Aquifer Test in Overlying or Underlying Aquifers		A - D	Appears to be applicable if tests are prolonged. (Hantush, 1961; Neuman and Witherspoon, 1972)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 4-2

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HYDROGEOLOGIC MEASUREMENT TECHNIQUE

Parameter	Measurement Techniques	Purpose	Stage[1/]	Remarks
Permeability Continuity (Homogeneity)	Geologic Mapping of Strata and Fracture Systems (Refer to Table 2-1)		A, B	Qualitative appraisal of permeability is possible, but better interpretation is needed.
	Correlation of Borehole Logs (Refer to Table 2-1)		A, B	Applicable for identifying aquifers. Not proven for identifying fracture permeability paths, but may be possible.
	Broadway Effects in Pumping Tests		A, B	Pumping tests in which water level in observation wells is monitored during pumping. (Ferris and others, 1962)
	Mine Drainage Tests		C, D	Water balance is estimated for a mine in which all water pumped out of the mine is monitored against measured quantities entering the mine over time. (O'Brien et al., 1978)
	Computer Modeling of Variability of Fracture Permeability		A - D	State-of-the-art questionable at present. (O'Brien et al., 1978)
Directional Permeability (Isotropy)	Geologic Mapping of Strata and Fracture Systems		A, B	Appears applicable. Qualitative appraisal to determine permeability conditions. (O'Brien et al., 1978; Louis and Pernot, 1972)
	Oriented Cores		A, B	Appears applicable. Qualitative appraisal to determine permeability conditions. (O'Brien et al., 1978)
	Borehole Camera		A, B	Appears applicable. Qualitative appraisal to determine permeability conditions. (O'Brien et al., 1978)
	Multiple Hole Injection Test		B	Test wells in field. Requires more drilling than is desirable. Method used only once, not on bedded salt. (O'Brien et al., 1978)
	Increasing Packer Spacing in Orthogonal Boreholes		B	Pumping tests in drilled boreholes. Not a proven method as yet. (O'Brien et al., 1978)

[1/] Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 4-2

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HYDROGEOLOGIC MEASUREMENT TECHNIQUE

Parameter	Measurement Techniques	Purpose	Stage[1/]	Remarks
Directional Permeability (Cont'd.)	Modelling		B	Results of experiments in crystalline rock performed by Gale and Witherspoon (1978) appear to be applicable to bedded salt.
Effect of Stress on Permeability	Laboratory Fracture Tests	Measure changes in flow parameters	B - D	Requires research and development in state-of-the-art. (Snow, 1968; O'Brien et al., 1978)
Pressure Gradient	Multiple Water-Level Measurements in Several Holes and/or Several Zones in the Same Hole	Monitor flow direction and rate	A - D	Field monitoring of water levels in wells. Many applicable subtechniques available for aquifers. Requires advances in state-of-the-art for low permeability materials. (O'Brien et al., 1978)
Pressure Gradient Changes	Repetitive Water Level Changes	Monitor changes in hydrologic boundaries and properties	A - D	Field monitoring of water levels in wells. Many applicable subtechniques available for aquifers. Requires advance in state-of-the-art for low permeability materials. (O'Brien et al., 1978)
	Continuous Water-Level Changes	Identify changes in hydrologic boundaries and properties	A - D	Field monitoring of water levels in wells. Many applicable subtechniques available for aquifers. Requires advance in state-of-the-art for low-permeability materials. (O'Brien et al., 1978)
Porosity	Laboratory Methods	Fluid velocity, porosity, effective porosity	A - D	Laboratory tests to determine total porosity and amount of fissure porosity, noninterconnected porosity and effective porosity. Sample not likely to be representative of rock. (Meinzer, 1923; Stearns, 1928; Morris and Johnson, 1967)
	Core Analysis	Fluid velocity porosity, effective porosity	A - D	Qualitative assessement of porosity. Sample not likely to be representative of rock. (Snow, 1968)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 4-2
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HYDROGEOLOGIC MEASUREMENT TECHNIQUE

Parameter	Measurement Techniques	Purpose	Stage[1/]	Remarks
Velocity	Tracers	Velocity of contaminant movement	B - D	Field or laboratory tests to determine paths of flow by injecting tracer materials into flow system. No assurance tracer and contaminant will have same velocity unless contaminant is used for the tracer. (Wenzel and Fishel, 1942)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 4-3

WATER QUALITY MEASUREMENTS: WATER SAMPLING TECHNIQUES

Water Sampling Techniques	Remarks
Sampling cups in unsaturated regions:	Operates at pressures greater than about -1.0 atmosphere. Cup inhibits inflow of suspended solids and bacteria, making test for biochemical oxygen demand (BOD) on collected samples inaccurate. Excessive vacuum application may influence soil water movement in the vicinity of the cup. (Everett et al., 1976):
• Suction cup	Uses vacuum withdrawal. Requires good contact between soil and cup. (Everett et al., 1976)
• Suction cup assembly (Parizek and Lane, 1970)	Permits installation of more than one unit in a hole. Does not require intimate contact between cup and soil. Precludes clogging of cup by colloidal material. Provides sampling at greater depth than suction cup (above). Solutions may be forced back into the soil during the release of vacuum and application of pressure. Sampling depths range to 15 meters. (Everett et al., 1976)
• Porous cup assembly	Only one unit is installed per hole. No back flow into soil during release of vacuum and application of pressure. Sampling depths range to 36 meters. (Everett et al., 1976; Wood, 1973)
Sampling devices in saturated regions:	
• Bailer	Not capable of sampling at selected depth. Normally samples surface portion. (EPA, 1976; Everett et al., 1976)
• Thief sampler	Water collected at selected depths below water table. (EPA, 1976; Everett et al., 1976)
• Inlet and outflow line assembly	No need to remove sampler from well between samplings at different depths below water table. Air introduced into sample may interfere with subsequent chemical analyses. (Everett et al, 1976)
• Fiberglass probes	Samples through outflow line via vacuum pump; allows discrete simultaneous sampling at several depths to minimize interference with natural flow within the sampling region. (Hansen and Harris, 1974)
• Pump	Depth interval to be sampled is segregated by sealing-off the rest of the well and pumping. (EPA, 1976)
• Lysimeter	Pan sampler at different depths collects leachate; relatively expensive construction involved. (Parizek and Lane, 1970)
• 3-liter Kemmerer or Van Dorn style water sampler	Can be used for surface-water sampling and ground-water collection in wells. (Langford et al., 1977)

TABLE 4-4

WATER QUALITY MEASUREMENTS: CHEMICAL PARAMETERS[1/]

Chemical Parameters	Measurement Techniques	Units	Remarks
Alkalinity	Titration method	mg/l	Determine total alkalinity. (Langford et al., 1977)
Biochemical Oxygen Demand (BOD)	BOD test (5 days, 20°C)		Dissolved oxygen in the BOD test may be determined by either the Modified Winkler with Full-Bottle Technique or the Probe Method. (Ballinger et al., 1974)
Chemical Oxygen Demand (COD)	COD test		Traces of organic material may interfere. (Ballinger et al., 1974)
Dissolved Oxygen	Modified Winkler with Full-Bottle Technique		Nitrate ion, ferrous iron and organic matter interfere. (Ballinger et al., 1974)
	Probe method		Most of the common interferences found in the Modified Winkler Method may be overcome. (Ballinger et al., 1974)
Hardness	Titration method		Iron, copper, aluminum, cobalt and nickel interfere. (Langford et al., 1977; Hach Chemical Co., 1977)
Hydrogen Ion Concentration (pH)	Electrode method	pH values	Oil and greases may coat the electrode and interfere. Precision: for surface water sample at an average pH of 7.7, the standard deviation was ± 0.1. (Ballinger et al., 1974; Hach Chemical Co., 1977)
Oxidation-reduction Potential	Redox measuring device	Redox potential	Application range: -700 to +700 mV. (Langford et al., 1977)
Salinity	Salinity sensor		In-situ measurement relating salt concentration to specific conductivity of soil solution. Temperature dependent. Not used at soil-water pressure less than -2 atmospheres. (Everett et al., 1976)
Common Ions:			Optimum concentration range (Ballinger et al., 1974)
Calcium	Atomic absorption methods	mg/l	0.02 - 2 mg/l
Magnesium			0.02 - 2
Potassium			0.01 - 2
Sodium			0.03 - 1
Bicarbonate	Electrometric titration - glass electrode		Precision: Standard deviation = 1.2 mg/l at concentration of 34.7 mg/l. (Langford et al., 1977)

1/ Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

TABLE 4-4

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WATER QUALITY MEASUREMENTS: CHEMICAL PARAMETERS[1/]

Chemical Parameters	Measurement Techniques	Units	Remarks
Common Ions: (Cont'd.)	Electrometric Titration - Glass Electrode (Cont'd.)	mg/l	
Carbonate			Application range: 0 to 200 mg/l. (Langford et al., 1977)
Chloride	Automated method		Sulphites interfere. Applicable range: 1 - 250 mg/l. (Ballinger et al., 1974)
Chlorine, free residual	DPD (N,N-diethyl-p-phenylene-diamine) indicator		Bromine, iodine, ozone and oxidized forms of manganese may interfere. (Hach Chemical Co., 1977; Langford et al., 1977)
Chlorine, total residual	Amperometric titration		Not for samples containing above 5 mg/l total residual chlorine. Significant amounts of organic matter may interfere. (Ballinger et al., 1974)
Nutrients:			
Nitrate	Colorimetric with brucine-sulphuric acid		Strong oxidizing or reducing agents and high content of organic matter interfere. (ASTM, 1978)
Phosphate	Colorimetric method		Application range: 0.01 to 0.5 mg/l. Precision: Standard deviation = 0.02 mg/l at concentration of 0.38 mg/l. (Langford et al., 1977)
Trace Elements:			
Cadmium	Atomic absorption		Optimum concentration range: 0.05-2 mg/l. (Ballinger et al., 1974)
Copper	Atomic absorption		Optimum concentration Orange: 0.2-10 mg/l. (Ballinger et al., 1974)
	Colorimetric: neo-cuproine		Applicab.e to ocean water and brines. (Langford et al., 1977)
Iron	Atomic absorption		Optimum concentration range: 0.3-10 mg/l. (Ballinger et al., 1974); Subject to silica interference. (ASTM, 1978)

[1/] Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

TABLE 4-4
Sheet 3 of 5

WATER QUALITY MEASUREMENTS: CHEMICAL PARAMETERS[1/]

Chemical Parameters	Measurement Techniques	Units	Remarks
Trace Elements: (Cont'd.)		mg/l	
	Colorimetric: bipyridine		Application range: 10 to 4000 μg/l. Precision: Standard deviation = 19 μg/l at concentration of 397 μg/l. (Langford et al., 1977)
Lead	Atomic absorption		Optimum concentration range: 1-20 mg/l. (Ballinger et al., 1974)
	Colorimetric: Dithizone method		Application range: 10 to 400 μg/l. Precision: Relative standard deviation = 42.1% at concentration of 70 μg/l (Langford et al., 1977)
Manganese	Atomic absorption		Optimum concentration range: 0.1-10 mg/l. (Ballinger et al., 1974)
	Colorimetric: Persulfate		Application range: 25 to 15,000 μg/l. (Langford et al., 1977)
Mercury	Atomic absorption (cold vapor technique)		Optimum concentration range: 0.0002-0.01 mg/l. (Ballinger et al., 1974)
Molybdenum	Atomic absorption		Optimum concentration range: 0.5-20 mg/l. (Ballinger et al., 1974)
Selenium	Atomic absorption (gaseous hydride method)		Optimum concentration range: 0.002-0.02 mg/l. (Ballinger et al., 1974)
	Colorimetric: Diaminobenzidine extraction method		Application range: 1 to 100 μg/l. (Langford et al., 1977)
Silver	Atomic absorption		Optimum concentration range: 0.1-4 mg/l. (Ballinger et al., 1974)
Zinc	Atomic absorption		Optimum concentration range: 0.05-2 mg/l. (Ballinger et al., 1974)
	Colorimetric with Zincon		Cadmium, aluminum, manganese, cobalt, nickel and copper may interfere. (ASTM, 1978)
Total organic carbon	Combustion infrared		Application range: 2 to 200 mg/l. (Langford et al., 1977)

1/ Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

TABLE 4-4

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WATER QUALITY MEASUREMENTS: CHEMICAL PARAMETERS[1/]

Chemical Parameters	Measurement Techniques	Units	Remarks
Dissolved Gases:		mg/l	
Ammonia	Ion selective electrode		Application range: 0.03 to 1400 mg/l. (Langford et al., 1977)
Carbon dioxide, total	Precise evolution method		Concentration between 1 and 50 mg/l determined on a 200-ml sample with precision of 0.25 mg/l and in concentrations above 50 mg/l with precision of 0.5 mg/l. (ASTM, 1978)
Hydrogen sulphide	Methylene blue method		Sulphite, thiosulphate and hydrosulphite interfere. (APHA, 1975)
Methane	Gas chromatography		Applicable to fresh and brackish water. (Langford et al., 1977)
Nitrogen	Gas chromatography with thermal conductivity detector		Application range: 1 to 33 mg/l; higher concentrations by instrument attenuation. (Langford et al., 1977)
Radiochemical Parameters:			
Alpha activity, gross	Evaporation; counting with proportional or scintillation detector	pCi/l	Detection limit: 30 pCi for 60-min. count (3 pCi/l). Precision: 25% at 20 pCi/l. (ASTM, 1978; Langford et al., 1977)
Beta activity, gross	Evaporation; counting with low background, thin window beta detector		Detection limit: 10 pCi/l 100-ml sample, 60-min. count. Precision: Approximately 25% at 50 pCi/l. (ASTM, 1978; Langford et al., 1977)
Cesium-137	Carrier-free batch type ion exchange; filter, mount and beta count		Detection limit: 10 pCi using thin window flowing gas proportional counter with counts approximately equal to 2 cpm above background (1 pCi/l). Precision: Estimated ± 75% at 10 pCi/l. (Langford et al., 1977; Thatcher et al., 1977)
Gamma activity, gross	Gross gamma counting		Detection limit: 1 nCi/l, 10-min. count on 3" x 3" NaI(Tl) well crystal. Precision: ± 3% at 40 nCi/l. (ASTM, 1978; Langford et al., 1977)

1/ Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

TABLE 4-4

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WATER QUALITY MEASUREMENTS: CHEMICAL PARAMETERS[1/]

Chemical Parameters	Measurement Techniques	Units	Remarks
Radiochemical Parameters: (Continued)			
Lead-210	Extraction; beta counting or combined alpha beta count	pCi/l	Detection limit: 30 pCi (3.0 pCi/l). Precision: 1.8% at 2400 pCi level. Relative standard deviation of 5.1% on quadruplicate analysis of lead-210 standards. (Langford et al., 1977; Talvitie and Garcia, 1965)
Radium-226, by Radon	Coprecipitation with barium sulphate; radon determined by alpha scintillation		Detection limit: 0.01 pCi/l. Pr cision: + 20% at 0.1 pCi/l; + 10% for concentrations > 0.10 pCi/l. (Langford et al., 1977; Thatcher et al., 1977)
Strontium-90	Precipitation and beta counting		Detection limit and precision not given. (APHA, 1971; Association of Official Anal, 'cal Chemists, 1975; Langford et al., 1977)
Thorium	Barium sulphate precipitation and fluorometry		Detection limit: 0.1 μg/l on 100-ml sample. Precision: 10% on 0.1 μg, 0.5% on 5 μg. (Langford et al., 1978; Sill and Willis, 1962, 1964)
Tritium	Azeotropic distillation and liquid scintillation counting		Detection limit: 200 pCi/l for a 200-min. count (2 sigma counting error = 100%). Precision: + 10% at 2000 pCi/l, + 200 pCi/l below 2000 pCi/l (1 sigma). (ASTM, 1978; Johns, 1975; Langford et al., 1977)
Uranium	Determine uranium by comparison of reflected fluorescence from spiked and unspiked residues fused with sodium-potassium carbonate-fluoride flux		Detection limit: 0.5 μg/l. Precision: + 20% at 0.5 μg/l level. (Langford et al., 1977; Thatcher et al., 1977)
	Coprecipitation of uranium with aluminum phosphate. Dry precipitate and dissolve in magnesium-nitrate-nitric acid solution. Extract the uranium into ether, evaporate and fuse the residue with sodium-potassium carbonate-flouride as in direct procedure		Detection limit: 0.01 μg/l. Precision: 100% at 0.01 μg/l minimum. (Thatcher et al., 1977)

[1/] Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

TABLE 4-5

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WATER QUALITY MEASUREMENTS: PHYSICAL PARAMETERS[1/]

Physical Parameters	Measurement Techniques	Unit	Remarks
Color	Platinum-Cobalt method	Platinum-Cobalt units	Method is pH dependent. Slight amounts of turbidity interfere. (Ballinger et al., 1974; Langford et al., 1977)
	Spectrophotometric		Slight amounts of turbidity interfere. (Ballinger et al., 1974)
Conductance, specific	Conductivity meter	mhos/cm at 25°C	Samples preferably analyzed at 25°C. If not, temperature corrections are made and results reported at 25°C. (Ballinger et al., 1977)
			Precision: Standard deviation not to exceed 5% of measured value. (Langford et al., 1977)
Odor, threshold	Consistent Series Method	Threshold odor units	Compare results on chlorinated and dechlorinated samples to eliminate chlorine interference; sample stored in glass bottles or teflon-lined closures. (Ballinger et al., 1974; Langford et al., 1977)
Resistivity	Wheatstone bridge	Ohm-meters	Applicable range: 0.01 to 10 ohm-meters; applicable for ocean water and brine. (Langford et al., 1977)
Total dissolved solids (TDS)	Gravimetric method	mg/l	Highly mineralized waters containing significant concentrations of calcium, magnesium, chloride and/or sulphate require prolonged drying. (Ballinger et al., 1974)
			Applicable range: 10 to 20,000 mg/l. (Langford et al., 1977)
Total suspended solids	Gravimetric method		Applicable range: 10 to 20,000 mg/l. Precision: Approximately ± 4 mg/l or 5%. (APHA, 1971; Langford et al., 1977)
Total volatile residue	Gravimetric method		Precision: Standard deviation of ± 11 mg/l at 170 mg/l volatile residue concentration. (Ballinger et al., 1974)
			Applicable range: 10 to 20,000 mg/l. (Langford et al., 1977)

1/ Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

TABLE 4-5
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WATER QUALITY MEASUREMENTS: PHYSICAL PARAMETERS[1/]

Physical Parameters	Measurement Techniques	Unit	Remarks
Specific gravity	Balance method	Dimensionless	Precision: ± 0.0001. (American Petroleum Institute, 1968; Langford et al., 1977)
	Pycnometer		Precision: ± 0.00005. (American Petroleum Institute, 1968; Langford et al., 1977)
	Hydrometer		Precision: ± 0.001. (American Petroleum Institute, 1968; Langford et al., 1977).
Turbidity	Nephelometric	Formazin turbidity units (FTU)	Applicable range: 0 to 40 FTU. (Langford et al., 1977)
Temperature	Thermometer	°C	
	Mercury-in-steel sea thermograph		For recording water temperature at different depths in lakes, reservoirs. (Middleton and Spilhaus, 1953)
Light penetration	Lowering a disk	Secchi depth	A horizontal 8-cm-diameter black and white disk is lowered into the water until it disappears. (Lytle et al., 1979)
	Using a photocell	Extinction coefficient	Slope of the light absorption curve is measured by means of a photocell lowered into the water. More detailed study than disk lowering. (Lytle et al., 1979)
Light transmissivity	Transmissometer	Relative turbidity	To detect the percentage of light transmitted by a source which is received by a photocell. Capable of measuring at different depths. (Lind, 1974; Lytle et al., 1979; Welch, 1948)

1/ Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

WATER QUALITY MEASUREMENTS: PHYSICAL PARAMETERS[1/]

Physical Parameters	Measurement Techniques	Unit	Remarks
Suspended sediment	Evaporation	Concentration: mg/l	Method used where the sediment concentration exceeds 2,000 mg/l - 10,000 mg/l. Requires a correction for samples having a low concentration of sediment if the dissolved solids content is high. (ASCE Task Committee, 1975)
	Filtration method		Best method for lower concentrations. The use of crucible in the filtration method has the following advantages over the use of the evaporating disk in the evaporation method: (1) It is lighter in weight and consumes less oven and desiccator space; (2) its tare weight is less likely to change during weighing due to absorption of moisture from air; and (3) dissolved material passes through the crucible and thus eliminates the need for a dissolved-solids correction. (ASCE Task Committee, 1975)
	Displacement method		Accuracy depends on the sensitivity of the balance in relation to the total weight of solids in the sample as well as the accuracy of the estimate for specific weight of solids. Method limited to samples from laboratory sediment experiments, especially where it is not desirable to oven dry the sediment. (ASCE Task Committee, 1975; Interagency Committee, 1941)
	Particle-size analysis	Particle-size distribution	Used when sediment data are used to estimate deposited volume. The wet-sieve method, which requires that the sample not be dried prior to sieving, is preferred over the dry-sieve method. (Guy, 1969)
	• Sieve method		Sieving is limited to those sizes coarser than 0.0625 mm. (Lytle et al., 1979)

1/ Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D), Stages.

TABLE 4-5

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WATER QUALITY MEASUREMENTS: PHYSICAL PARAMETERS[1/]

Physical Parameters	Measurement Techniques	Unit	Remarks
Suspended Sediment (Cont'd.)	Particle-size analysis (Cont'd.)		
	• Sedimentation methods	Particle-size distribution	Concentration of the sample analyzed by these methods has a considerable effect on the accuracy of analysis (Interagency Committee on Water Resources, 1943); therefore, samples should be split or diluted as follows:
			Method: Pipet — Concentration in Tube (mg/l): 2,000 - 5,000
			Method: BW tube — Concentration in Tube (mg/l): 1,000 - 10,000
			Method: VA tube — Concentration in Tube (mg/l): Total height of accumulation not to exceed 12 cm.
			Pipet and bottom-withdrawal tube (BW tube): For material finer than 0.062 mm.
			Visual-accumulation tube (VA tube): For material coarser than 0.062 mm. (Kisselman, 1974; Lytle et al., 1979)
Bed material	Particle-size analysis		Material coarser than sand (2.00 mm) should be analyzed by the sieve method. (ASTM, 1938). Coarse material may be analyzed by the photographic technique. (Ritter and Helley, 1969). Samples in the sand, silt and clay ranges may be analyzed according to the standard procedures described previously for suspended sediment. (Interagency Committee on Water Resources, 1943)
Soil temperature	Soil thermometers	°C	Used to measure soil temperature at different depths; thermometers with bent stems used for depths less than one foot. (Middleton and Spilhaus, 1953)

[1/] Applicable to Construction Authorization (B), Emplacement (C), and Decommissioning (D) Stages.

CHAPTER 5

THERMAL MEASUREMENT TECHNIQUES

5.1 INTRODUCTION

Thermal measurements are required to

- Evaluate rock heat effects on ground-water flow
- Evaluate rock behavior--including rock stresses, rock strength, rock creep properties, and long-term stability--in response to temperature changes
- Estimate underground (repository) behavior in response to a given waste storage scheme
- Analyze cooling requirements for the ventilation and other systems
- Monitor rock temperatures and repository heat flows during excavation, placement, and retrieval of waste to check design estimates and to warn of potential problems
- Monitor rock temperatures during and after decommissioning to check heat flows and temperatures and their effects upon ground-water flow and the surface environment.

Each canister emplaced in a repository in bedded salt will act as a long-term heat source. Following emplacement, heat will flow from the canister into adjacent rock with a resulting increase in rock temperature. With time, this heat will spread into the rock surrounding the storage area and eventually into the entire rock mass of the repository site. Moreover, this heat flow will depend upon the canister storage schedule, the thermal properties of the salt and other associated geologic strata, the ground-water conditions, the layout of tunnels and rooms, and other factors.

The flow of heat into the rocks will increase rock temperature within the repository. A temperature as high as $300^{\circ}F$ was estimated for rock around a storage room in bedded salt after a twenty-five-year period. This estimate was based upon the storage of high-level wastes contained in closely spaced canisters in a non-ventilated room (Science Applications, Inc., 1978).

The temperatures within a repository will be controlled by the heat transfer mechanisms, expressed in simplified terms by the equation

$$\text{Heat-In} + \text{Heat-Stored} = \text{Heat-Out}$$

Heat input will consist of the heat emitted from each canister. It will have a spatial distribution that will enlarge with time, depending upon the storage scheme. Heat output will occur by heat flow through rock and through ventilated openings to the earth's surface, through rock to aquifers where convection cells may be created, and finally, possibly through specially designed heat extraction systems.

Heat stored will be the thermal energy retained in the repository rock and will be represented by a rise in repository temperature. As long as heat input exceeds heat outflow, rock temperatures must rise. This means that rock temperatures can be controlled either by limiting the heat input or by lessening the restrictions on heat outflow. The heat input will depend on canister power and canister distribution. However, the heat generated in each canister will decay with time. The heat outflow will depend upon the thermal conductivity of the rocks, the ventilation system characteristics, the position of openings, and a complex of rock conditions imposed by the geologic setting.

The effects of a rise in rock temperature within a repository will result in

- a probable lowering of compressive strengths of the salt strata

- an increase in creep rates within the salt beds and possibly within non-salt beds

- an increase of rock stresses within the heated rock caused by thermal expansion

- a possible weakening of some rock strata due to temperature-induced chemical changes within the strata

- a possible weakening of some rock strata due to vaporization of pore water

- a possible disturbance of natural ground-water conditions above or below the repository due to heat-induced conversion flows within aquifers.

All of these results could adversely affect the containment capabilities of a waste repository in bedded salt by creating structural failures in the rock or repository seals, and by inducing ground-water currents that could carry contaminated material to the surface. For these reasons, capabilities to predict and monitor the thermal behavior of a repository are imperative.

One of the fundamental problems to be encountered in the design and operation of a repository will be the prediction and monitoring of repository temperatures. What rock temperature restrictions must be adopted in order to insure opening stability and canister retrievability? What ventilation air temperature restrictions must be adopted in order to insure the smooth operation of equipment and the health and safety of workers? Can these temperatures be predicted during the exploration and design phases? Can these temperatures be controlled by careful planning of canister emplacement and through operation of the ventilation scheme or other heat extraction systems? The answers to these questions depend solely on the prediction and monitoring of heat flow within the repository and the ability to measure the thermal parameters associated with that heat flow. These parameters are discussed in Appendix C, prefaced by a review of thermal behavior of materials.

5.2 MEASUREMENT TECHNIQUES

Laboratory and field measurement techniques are listed in Table 5-1. Until the present time, field techniques have been oriented toward geothermal energy and oil exploration where rock and soil temperatures are measured in surface boreholes. Additional work has been done in developing temperature and thermal conductivity probes for geophysical research programs investigating the earth's geothermal gradients.

The techniques available today can be used for the exploration and monitoring of a repository in bedded salt. However, there are many areas where improvements can be made, especially in temperature, thermal conductivity, and thermal capacity (specific heat) measurements in rocks with temperatures in the range of $200^{\circ}F$ and higher.

A. Temperature

Temperatures to an accuracy of $\pm 0.001^{\circ}C$ ($\pm 0.0018^{\circ}F$) can be measured on rock surfaces or in boreholes. These measurements are made by probes which contain a temperature sensing element. These elements are described in Table 5-1.

Temperature probes may be installed permanently upon rock walls or in boreholes, or they may be designed to be portable. Downhole probes have been fully developed for use in oil field and geothermal energy exploration. However, there are no special probe designs available for work in small boreholes underground, or for permanent emplacement on rock walls or in boreholes. The long-term stability of temperature probes for operation in high-temperature environments is not known.

Temperature measurements must be done with care if accuracy is desired. Readings should be taken after probe temperature equalizes with rock temperature. A probe in a borehole where water is flowing measures the temperature of the fluid, often different from the adjacent rock temperature. Temperatures taken during drilling operations may be affected by rock heating due to bit action and the friction of drill rods against the wall.

Temperature measurements taken on tunnel walls reflect the cooling of the wall by passing ventilation air. Several readings taken in boreholes drilled out from the wall can yield a cross section of heat flow toward the tunnel, and allow estimates of temperatures in deeper rock.

B. Thermal Conductivity

In-situ measurements of thermal conductivity are made by borehole probes. The idealized model is a cylindrical probe containing a heater and temperature-measuring elements placed in the rock. The heater is activated to supply a sudden, constant rate of heat to the rock. The temperature rise at the rock-probe contact is then monitored. Using the theory of heat transfer, one can obtain a relationship between temperature, heat output, time, and the thermal conductivity of the rock (Jaeger, 1965). Probes are designed to fit this model so that data analysis is tenable.

Probe data are analyzed by using graphical plots of temperature (T) vs. the natural logarithm of time (ln t). These plots show an initial nonlinear curve where the curve rises asymptotically toward a straight line. Once this asymptote has been reached, the thermal conductivity can be calculated. The conductivity equals the controlled heat flow rate divided by four times the slope of the line. This technique has been adapted to needle probes for soils and loose sediments, and to borehole probes for rocks (Beck, 1965).

For most rocks, the time period for the development of the asymptote is on the order of hours. To reduce this waiting time for probe measurements, Blackwell (1954) suggested a second method of data analysis. In this method the effects of the thermal resistance between the probe and rock are calculated and then subtracted from the temperature-time data. This leads to a more rapid development of the asymptote.

A third method of analyzing heat probe data has been suggested by Jaeger (1956). This method uses a set of exact solutions to the probe heat flow problem for various conductivity and specific heat (thermal capacity) values (Beck, Jaeger and Newstead, 1956). The solutions are plotted as a family of curves. The results of a probe test are then compared with these curves, and both thermal conductivity and specific heat can be determined. Sass (1961) reported good results with this method when special curve-fitting techniques were used in analyzing the data.

Two methods have been used to determine laboratory thermal conductivities: steady-state methods and transient methods. In the steady-state method a rock disk is sandwiched between two metal rods with known conductivity. One end of the system is heated at a lower temperature than the other end. Thermocouples measure temperatures along the rod. After steady-state heat flow is attained, measured temperatures are used to determine the heat flow in the rods and the temperature drop across the disk. Disk conductivity is calculated by dividing the heat flow across the disk by the temperature drop (Beck and Beck, 1958; Beck, 1965).

Transient methods are similar to the method described for in-situ tests. A heat source is activated upon a sample and temperature changes are recorded over time. From the graph of temperature vs. time and referring to a mathematical solution to the transient heat transfer problem, one can calculate conductivities. (For details, see Powell, 1957; Zierfuss, 1963; and Jaeger and Sass, 1964.) Transient methods can be performed more quickly than the steady-state method.

C. Rock Thermal Capacity (c)

In-situ determination of thermal capacity is obtainable from Jaeger's method of analysis of in-situ thermal conductivity probe data described above (Jaeger, 1956). Laboratory methods of thermal capacity determination for rocks are not standardized; however, standard methods used for other materials are applicable. (See Table 5-1 for references.) The effects of porosity, stress, pore water, temperature, and pore configuration upon specific heat have not been investigated, so that no data are available for the evaluation of laboratory values against in-situ values.

D. Heat Transfer Coefficient (h)

The literature revealed no efforts to measure heat transfer coefficients in tunnels or mine openings, nor any techniques for measuring these coefficients underground. To determine these heat transfer coefficients, the heat flow rate and temperature differential across a rock-face element must be ascertained. This determination involves measuring rock and air temperatures at the rock-air interface, and the total heat flow within the rock toward the face. The latter can be determined from the temperature gradient within the rock adjacent to the face by using the rock thermal conductivity. The air and rock temperatures can be determined with temperature probes. The heat flow per unit area times the temperature differential will give a local value of the heat transfer coefficient for a given air velocity, for a given tunnel, and for a given temperature gradient.

For rock, there exist no specifically designed laboratory methods to measure heat transfer coefficients. However, those tests used for building materials are probably applicable to rocks (ASTM, 1979 a, 1979 b, 1979 c); adaptations can be developed for testing repository rocks.

E. Diffusivity

Thermal diffusivity can be calculated from known values of thermal conductivity, weight density and specific heat, or it can be measured. There exist no in-situ methods to measure diffusivity in rocks.

Laboratory measurements of diffusivity can be made by methods similar to the standard method listed for carbon and graphite (ASTM, 1978 d). In this method, a heat pulse is applied to one side of a thin disk of carbon or graphite, and the temperature history of the reverse side is monitored over time. From a plot of temperature vs. time, diffusivity can be calculated. The method can be adapted to rocks, but testing techniques need to be developed.

F. Density

Density measurement techniques are discussed in Chapter 3, Rock Mechanics Measurement Techniques.

G. Emissivity

No in-situ techniques for measuring emissivity from rock surfaces have been found in the literature. However, two methods have been reported for measuring the total normal emittance from surfaces in general (Nelson, Leudke, and Bevans, 1966; Gaumer, Hohnstreeter, and Vanderschmidt, 1963). Both techniques employ portable meters that monitor predominantly infrared radiation emittance from surfaces.

No standard laboratory methods for measuring rock emissivity have been reported in the literature. Standard methods used for other materials are perhaps applicable (see Table 5-1).

H. Heat Flow

No instruments have been developed to measure and monitor heat flow in rocks. Some instruments have been developed for use in furnace walls. It is possible to develop borehole techniques to automatically record heat flow. Such an instrument would require multiple temperature measuring elements coupled with materials of known conductivity.

I. Thermoelastic Constants

As a rock mass is heated, it will expand. In general, this expansion will be anisotropic--that is, expansion will differ in different directions. The result will be an increase in the stresses in the repository rock due to heat expansion effects.

Thermoelastic constants can be measured in-situ using rock heaters. At this time, only one method of measurement has been reported in the literature (Board, Pratt and Voegele, 1979). In this method, a block of rock in the wall or floor of a tunnel is cut out on four sides, leaving slots for accepting flat heaters. The fifth side of the block is exposed to the tunnel opening while the sixth side is left attached to virgin rock. Heaters are then introduced into the slots and activated so that a uniform temperature field can be imposed upon the block. By measuring block expansion as a function of temperature, the thermoelastic constants of the block can be determined. Other in-situ tests using boreholes are possible, but research and development are needed.

Laboratory techniques all consist of measuring a sample's linear strains resulting from uniform change in sample temperatures. Strain gages, linear differential voltage transducers (LDVTs), and other transducers can be used to measure these strains. Standard laboratory techniques used for metals and ceramics are adaptable to rocks as referenced in Table 5-1.

J. Rock Thermochemical Properties

Chemical changes activated by temperature increases either release or absorb heat. This process of heat generation or absorption can be detected by an accurate monitoring of sample temperatures while a steadily increasing, externally induced temperature rise is imposed upon the sample. This technique of searching for temperature-sensitive heat sources or sinks is known as differentiated thermal analysis (DTA). No techniques exist for employing DTA upon rocks in situ, either on rock surfaces or within boreholes.

Standard laboratory techniques do exist and are used extensively in ceramic engineering and metallurgy (ASTM, 1978 k). These techniques have been adapted to rocks and soils.

K. Rock Thermomechanical Properties

Temperature can affect the elastic moduli, strength, yield point, creep rates, and failure behavior of rock. For in-situ conditions, the field tests noted in Table 3-1, Rock Mechanics Measurement Techniques, will produce the rock properties at the existing rock temperatures at the time of testing. For example, overcoring for measuring in-situ stresses will produce a total stress composed of material overburden effects, residual stresses, tectonic stresses, stresses due to openings, and stresses due to thermal expansion of the rock around the repository.

Laboratory tests are normally performed upon specimens at room temperature (68°F). However, thermal jackets can be made which fit over the specimen during testing. Complete control over a wide range of temperatures is possible both for uniaxial and triaxial testing conditions. This type of testing has been performed for many rocks, including salt (Serdengecti and Boozer, 1961; Lomenick and Bradshaw, 1969).

All work reported in this area has been in the nature of research. Standard tests may have to be developed for purposes of producing data for repository evaluation and monitoring.

5.3 SUMMARY AND CONCLUSIONS

Most experience with the measurement of rock temperature and thermophysical properties is limited to the geothermal energy industry, the petroleum industry, and to geophysical research into the earth's geothermal gradient. Additional experience exists in the mining industry, where deep, hot mines are encountered. Most measurements, however, have been limited to temperature and thermal conductivity determinations. As indicated by Table 5-1, both in-situ and laboratory techniques have been developed to measure these properties.

In most cases, in-situ measurements have been made through boreholes with specially designed probes. For temperatures below 200^{o}F, accurate measurements of temperature and thermal conductivity are possible with present techniques. At higher temperatures, instrument design becomes more difficult, due to the effects of temperature upon the probes themselves. For most high-temperature work, specialized temperature measurement probes are designed for a specific project.

No in-situ techniques designed specifically for underground use were found for measuring emissivity, thermal heat transfer coefficient, thermoelastic constants, thermochemical properties, or thermomechanical properties. Portable instruments do exist for measuring emissivity, operating for the most part in the infrared range of wavelengths. The measurement of all of the other parameters requires the development of new techniques.

Laboratory testing techniques exist for measuring all thermal parameters. Accurate values of all rock properties are obtainable, including thermal conductivity, thermal capacity, diffusivity, heat transfer coefficients, thermoelastic constants, heats of activation, activation temperatures, and thermomechanical properties.

Some of the laboratory techniques listed in Table 5-1 were developed for materials other than rocks. However, they can be adapted to rock testing without difficulty, and should be able to produce reliable, accurate data. Laboratory tests for measuring the thermal properties of rocks have not been standardized because research into the thermal behavior of rock under mine conditions has been generally neglected. The large amount of rock thermal data required for repository design warrants test standardization.

Present techniques need to be improved and new techniques need to be developed. In each case, efforts to accelerate the preparation of samples, the testing procedure and data analysis need to be made. In addition, the significant effects of porosity, pressure, temperature and pore water need to be accounted for in the testing techniques.

Schedule

Thermal measurements must be taken during each stage of repository development. In general, most rock physical characteristics will be determined during early stages of repository exploration and development, while, in later stages, temperature monitoring will predominate.

Site Selection (Stage A)

Thermal measurements made during the reconnaissance and exploration programs must be directed at collecting data that will outline the thermal characteristics of the site--viz., (1) in-situ measurements of all the thermal properties of the salt and its associated strata, including thermal conductivity (k), thermal capacity (c), diffusivity (K), and rock density (w); (2) measurement of rock and ground-water temperatures in boreholes to determine the basic geothermal heat flow pattern at the site.

Laboratory measurements will require the testing of rock core samples for all of the previously listed thermal properties, and additionally, the thermoelastic constants, the thermochemical properties, the thermo-mechanical properties, and the heat transfer coefficients.

All of these data can be used to evaluate and design underground facilities.

Construction (Stage B)

During Stage B, both exploration shafts and tunnels and development shafts and tunnels will be excavated. In-situ thermal tests can be designed and performed in tunnels and rooms during the exploration stage. Tests designed to heat the rocks and to determine in-situ conductivities and all the other properties can be planned and performed. These tests can include both heater tests in rooms to determine heat flow rates in the rocks, and ventilation tests to determine rock emissivity parameters and heat transfer coefficients under varying air-flow conditions.

As mine development progresses, permanent monitoring instrumentation can be installed and tested for accuracy and reliability. Additional thermal property data can be collected as the underground facility expands in size. Finally, new instrumentation can be developed and tested for use

Emplacement (Stage C)

During Stage C, waste emplacement begins, marking the initiation of heat flow into repository rock. During this stage, rock temperatures, ground-water temperatures, rock heat flow rates, changes in rock thermal properties, changes in rock stress, and the competency of rock around openings should be monitored. The in-situ data collected in the rocks adjacent to the initially stored canisters can be used to check design estimates.

As time passes and storage continues, temperature monitoring of the repository rocks at selected locations can be used to check rock temperatures against design specifications and to outline the heat flow pattern over time. Changes in heat flow patterns can serve to warn of future temperature rises.

Decommissioning (Stage D)

During and after decommissioning, temperature measurements can be made both from underground stations in the repository and from surface boreholes. These measurements can be made both with permanently installed instruments and with borehole probes. Physical properties will probably not need to be measured, having been previously determined. Monitoring ground-water temperatures will be especially important.

TABLE 5-1

Sheet 1 of 4

THERMAL MEASUREMENT TECHNIQUES

Parameter	Measurement Techniques	Purpose	Stage[1/]	Remarks
Temperature	Measuring Elements Placed in Probes	To determine temperatures of rocks and fluids, temperature gradients	A, B, C, D	Temperature measurements are used to: Determine existing rock and fluid temperatures Test in-situ thermal properties of rock Monitor rock and water heating over time (Jaeger, 1965)
	• Thermistor			Thermistors are excellent for normal temperature measurements in boreholes and underground openings. They are accurate and do not need a reference temperature. Dewar bottle can be placed in probe for reference temperature. (LASL, 1976; Conaway and Beck, 1977; Omega, 1979)
	• Thermocouple			For high-temperature applications in testing and monitoring, thermocouples are more reliable. They require a reference temperature. Dewar bottle can be placed in probe for reference temperature. (LASL, 1976; Omega, 1979)
	• Resistance Temperature Device (RTD)			Platinum resistance thermometers (RTDs) have high accuracy and reliability, particularly for monitoring applications. Like thermistors, they do not need a reference temperature. (Omega, 1979)
	• Maximum Temperature Recording Thermometer			Mercury thermometer equipped to measure and record highest temperature encountered. Requires removal from hole for reading.
	• Vibrating Wire Strain Gage			Gage may be inserted unstressed into borehole. Changes in vibration frequency of wire is a function of temperature. (Dreyer, 1978)
	• Carlson Meter			Similar to vibrating wire strain gage. (Terrametrics, 1979)

[1/] Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 5-1
Sheet 2 of 4

THERMAL MEASUREMENT TECHNIQUES

Parameter	Measurement Techniques	Purpose To determine:	Stage[1]	Remarks
In-Situ Thermal Conductivity	Thermal Needle	Soil conductivity	A, B, C	Needle pressed into soil has heat source and thermistor probes. Needle measures heat flux and temperatures between points. Can be calibrated to read thermal conductivity. (Bullard, 1954; Von Herzen and Uyeda, 1963)
	Borehole Thermal Probe	Borehole thermal conductivity meter	A, B, C	A borehole instrument for thermal conductivity has been used in vertical boreholes. Conductivity is calculated by dividing heat flow across a disk by temperature gradient. (Beck, 1965; Jaeger and Sass, 1964)
Laboratory Thermal Conductivity	Laboratory Split Bar Apparatus	Rock thermal conductivity	A, B, C	Laboratory method for measuring coefficient of thermal conductivity. Heat flux is passed through a rock disk. Flux rate vs. time is measured. (Birch and Clark, 1940; Beck, 1965; Walsh and Decker, 1966; LASL, 1976; ASTM, 1978 a, b)
	Hollow Rock Core Method			A rock cylinder with a hole drilled down the center is used in this test. The cylinder is insulated on the ends and a heater is placed in the central hole. By measuring temperatures on the hole surface and outer cylinder surface, thermal conductivity can be measured. Tests can be done in triaxial cell. (Heard, 1979)
	Laser Pulse Method	Thermal conductivity, thermal capacity, diffusivity	A, B, C	Laser pulse technique proposed to determine rock physical properties. Ruby laser beam is pulsed against a rock core, introducing a known quantity of heat into sample. Temperatures on core are monitored over time. Results are analyzed by computer program. Status unknown. [Office of Waste Isolation (OWI), 1976, p. 61]
	Laboratory Plate Method	Thermal conductivity, diffusivity	A, B, C	Split-bar apparatus interfaced with a computer for quick calculations. System designed to operate with thermal pulse and in steady-state mode. (OWI, 1976, p. 61)
Thermal Conductance	Laboratory Methods • Guarded hot plate method • Guarded hot box method • Heat flow meter method	Thermal conductance	A, B, C	The methods measure the thermal conductance of insulating and building materials. Conductance is heat flow across a plate of material divided by the plate area and the temperature drop. The total temperature drop includes conductivity losses and surface heat transfer losses. (ASTM, 1979a, b, c)

[1] Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

TABLE 5-1

Sheet 3 of 4

THERMAL MEASUREMENT TECHNIQUES

Parameter	Measurement Techniques	Purpose To determine:	Stage[1/]	Remarks
Heat Capacity Specific Heat	Laboratory Calorimeter	Thermal capacity (specific heat)	A, B, C	Thermal capacity is measured on samples in the laboratory. Values are used to evaluate time constants associated with rock and salt heating. (ASTM, 1978)
	Borehole Thermal Probe	In-situ specific heat	A, B, C	Same probe used to determine thermal conductivity is used but data interpretation follows Jaeger. (Jaeger, 1956)
Moisture	Laboratory In-Situ Moisture Determination	Heating effects and moisture changes with temperature		Thermal conductivity and heat capacity strongly depend on moisture content. Moisture must be measured to evaluate the thermal properties of the repository. After waste emplacement, moisture can be monitored to determine heating effects on ground-water movements.
Diffusivity	Thermal Pole Method	Laboratory diffusivity	A, B, C	A thin disk is heated on one side by a lamp for an instant. Temperature of reverse side of disk is then monitored over time. Diffusivity is calculated from slope of 'T' vs. 't' curve. (ASTM, 1978d) No in-situ diffusivity tests exist at this time. Laboratory diffusivity will be affected by moisture and cracking.
Emissivity	Laboratory Spectral Analysis	Coefficient of emissivity of rock surface	A, B	Determine emissivity of a rock face with respect to temperature. Coefficient of emissivity (e) equals total emission of surface divided by black body emission at same temperature. Emissivity can be used to calculate heat transfer between rock and ventilation air. (ASTM, 1978e)
	Inspection-Meter Techniques		A, B	Portable instruments measure emissivity from any surface including rock. Instrument characteristics and accuracy for rock are not known. (ASTM, 1978f) Instruments available are: Emissometer, Lion Research Co., Cambridge, Mass. (Gaumer, Hohnstreeter and Vanderschmidt, 1963) Gier Dunkle Instruments, Inc., Santa Barbara, Calif. (Nelson, Leudke and Bevans, 1966)

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authori[illegible]ation.

TABLE 5-1

Sheet 4 of 4

THERMAL MEASUREMENT TECHNIQUES

Parameter	Measurement Techniques	Purpose	Stage[1/]	Remarks
Heat Flow	Heat Flow Meter	Monitor in-situ heat flow	B, C	Heat flow through a given area can be monitored directly by using several thermal probes in conjunction with materials of known thermal properties all set into a unit which can be placed within a material mass. No instruments of this type are known for rock. They have been used in furnace walls. (ASTM, 1978g, h)
Thermal Expansion	Laboratory Tests	Determine coefficient of thermal expansion	A, B, C	Evaluation of repository heating effects. Rocks expand upon heating and, if contained, will change state of stress in the repository. Expansion is dependent upon temperature, porosity and porewater. (ASTM, 1978i,j)
Thermochemical Properties	Laboratory Tests	Determine heats of activation and temperatures of activation for chemical	A, B	A rock sample is subjected to a slow, steadily increasing temperature source. Anomalous temperatures are monitored during the test period. Anomalies result from internal chemical changes caused by vaporization of porewater, released hydrated water, oxidation processes, etc. No known in-situ tests exist. (ASTM, 1978k)
Thermomechanical Properites	Specialized Laboratory Tests	Determine effects of temperature on properties	A, B	Temperature affects all of the rock properties. No standard tests exist for rocks. Testing techniques can be adapted from past research work and testing performed for other materials. Parameters to consider: • Thermal conductivity • Specific heat • Diffusivity • Emissivity • Strength • Elastic moduli • Creep coefficients • Stress • Displacement
Thermal Cracking	Laboratory and In-Situ Measurements		A, B, C	Determine effects of heating on integrity of repository. In-situ heater tests are required with measurement of resulting stress, strain, cracking, and temperature rise. Acoustical emission events and their amplitudes can be recorded to monitor cracking activity over time.

1/ Repository Development Stage: A = Site Selection, B = Construction Authorization, C = Emplacement Authorization, D = Decommissioning Authorization.

REFERENCES

Abel, J. F. and Lee, F. T., 1973, Stress changes ahead of an advancing tunnel: Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 10, p. 673-697.

Absi, E. and Seguin, M., 1967, Le nouveau géoextensomètre: Suppl. Annales de L'Institut Technique du Bâtiment et des Travaux Publics, no. 235-236, July-Aug. 1967, p. 1151-1168.

Acker, W. L., 1974, Basic procedures for soil sampling and core drilling: Scranton, PA, Acker Drill Co., 246 p.

Ackerman, J., 1973, Digital compilation of aeromagnetic data (Abstract). Geophysics, v. 38, p. 1189.

Adler, L. H., 1970, Evaluating double elasticity in drill cores under flexure: Int. J. Rock Mech. Min. Sci., v. 7, p. 357-370.

Aero Service Corporation, 1978, SAR Synthetic Aperture Radar: Houston, Texas.

Agarwal, R. K. and Boshkov, S., 1966, Theory of the 'soft inclusion' as a deformation gauge in boreholes: Int. J. Rock Mech. Min. Sci., v. 3, p. 319-323.

Ageton, R. W., 1967, Deep mine stress determinations using flatjacks and borehole deformation methods: U.S. Bureau of Mines, RI 6887.

Aitken, M. J., 1961, Physics and archaeology: London, Interscience.

Alas, M., 1968, Dilatomètres de sondage: Int. Symp. on Rock Mechanics, Madrid.

American Petroleum Institute, 1968, API Recommended practice for analysis of oil field waters, API RP 45, 2nd ed.: Dallas, American Petroleum Institute, p. 9-10.

American Public Health Association (APHA), 1971, Standard methods for the examination of water and wastewater, 13th Edition: Washington, D.C., American Public Health Association, 874 p.

____, 1975, Standard methods for the examination of water and wastewater, 14th Edition: Washington, D.C., American Public Health Association, p. 503.

American Society for Testing and Materials (ASTM), 1938, Designation C136-38T, Tentative method of test for sieve analysis of fine and coarse aggregates: Proc., v. 38-I, p. 808-810.

____, 1969, Determination of the in situ modulus of deformation of rock: ASTM STP 477.

____, 1978, *Water: Annual Book of ASTM Standards*, Part 31, 1232 p.

____, 1978a, Standard C202-71, Thermal conductivity of refractory brick: ASTM 1978 Annual Book of Standards, part 17.

____, 1978b, Standard C201, Thermal conductivity of refractories: ASTM 1978 Annual Book of Standards, part 17.

____, 1978c, Standard D2766, Specific heat of liquids and solids: ASTM 1978 Annual Book of Standards, part 24.

____, 1978d, Standard C714, Thermal diffusivity of carbon and graphite by a thermal pulse method: ASTM 1978 Annual Book of Standards, part 17.

____, 1978e, Standard E423-71, Normal spectral emittance at elevated temperature of nonconducting specimens: ASTM 1978 Annual Book of Standards, part 40.

____, 1978f, Total emittance of surfaces using inspection-meter techniques: ASTM 1978 Annual Book of Standards, part 41.

____, 1978g, Measurement of heat flux using a copper constantan circular foil heat flux gage: ASTM 1978 Annual Book of Standards, part 41.

____, 1978h, Standard E469-73, Measuring heat flux using a multiple water calorimeter: ASTM 1978 Annual Book of Standards, part 41.

____, 1978i, Standard B95-39, Linear expansion of metals: ASTM 1978 Annual Book of Standards, part 10.

____, 1978j, Standard E289-70, Linear thermal expansion of rigid solids with vitreous silica dilatometer: ASTM 1978 Annual Book of Standards, part 10.

____, 1978k, Standard E474, Assessing the thermal stability of chemicals by methods of differential thermal analysis: ASTM 1978 Annual Book of Standards, part 41.

____, 1978l, Standard D2938-71a, Unconfined compressive strength of intact rock core specimens: ASTM 1978 Annual Book of Standards, part 19.

____, 1978m, Standard D2664-67 (1974), Triaxial compressive strength of unchained rock core specimens without pore pressure measurements: ASTM 1978 Annual Book of Standards.

____, 1978n, Standard D2936-71, Direct tensile strength of intact rock: ASTM 1978 Annual Book of Standards, part 19.

____, 1979a, Standard C236, Steady state thermal transmission properties by means of the guarded hot plate method: ASTM 1979 Annual Book of Standards, part 44.

____, 1979b, Standard C518, Steady state thermal transmission properties by means of the heat flow meter: ASTM 1979 Annual Book of Standards, part 44.

____, 1979c, Standard C518, Thermal conductance and transmittance of built-up sections by means of the guarded hot box method: ASTM 1979 Annual Book of Standards, part 44.

American Society of Civil Engineers (ASCE), 1974, Subsurface mining for underground excavation and heavy construction: Proceedings of a Specialty Conference held at New England College, Henniker, N.H., Aug. 11-16, 1974.

American Society of Civil Engineers (ASCE) Task Committee for the Preparation of the Manual on Sedimentation, Sedimentation Committee of the Hydraulics Division, V. A. Vanoni, ed., 1975, Sedimentation engineering: *New York, Headquarters of the Society, p. 403-428.*

American Society of Civil Engineers (ASCE), The Committee of the Surveying and Mapping Division on Control Surveys, 1940, Horizontal control surveys to supplement the fundamental net: ASCE Manual of Engineering Practice, no. 20.

American Society of Photogrammetry, 1975, Manual of remote sensing: Keuffel and Esser Company.

American Water Works Association, 1973, Ground water, Manual M21: New York, AWWA.

Anuta, P. E., 1977, Computer-assisted analysis techniques for remote sensing data interpretation: Geophysics, v. 42, no. 3, p. 468-481.

Arzi, A. A., 1975, Microgravimetry for engineering applications. Geophys. Prosp., v. 23, p. 408-425.

Asada, T., 1957, Observations of near-by micro-earthquakes with ultrasensitive seismometers: J. Phys. Earth, v. 5, p. 83-113.

Association of Official Analytical Chemists, 1975, Official methods of analysis of the Association of Official Analytical Chemists, 12th ed.: Washington, D.C.

Badgley, P. C., 1959, Structural methods for the exploration geologist: New York, Harper, 280 p.

Banks, D. C., 1972, In situ measurements of permeability in basalt: Int. Soc. Rock Mech., and Int. Assoc. Engr. Geol., Proc. of the Symp. on Percolation Through Fissured Salt, Stuttgart.

Barla, G. and Wane, M. T., 1970, Stress-relief method in anisotropic rocks by means of gauges applied to the end of a borehole: Int. J. Rock Mech. Min. Sci., v. 7, p. 171-182.

Barr, A., 1960, Beiträge zu Problemen der Gebirgsdruckmessung und Gebirgsmechanik im Kali-und Steinsalzbergbau: Bergakademie No. 12, p. 444.

Barr, C. A., 1972, Determination of stresses in salt and potash mines for application to mine design: Saskatchewan Research Council.

____, 1977, Applied salt-rock mechanics, I: The in-situ behaviour of salt rocks: Amsterdam, Elsevier.

Barretto, P.M.C., 1975, Radon-222 emanation characteristics of rocks and minerals, in Radon in uranium mining: Vienna IAEA, p. 129-150.

Bates, R. G., 1964, Natural gamma aeroradioactivity of the national reactor testing station area, Idaho: U.S. Geol. Survey, Geophys. Investigation Map GP-446.

Beck, A. E., 1965, Techniques of measuring heat flow on land, in Lee, W. H. K., ed., Terrestial heat flow: Washington, American Geophysical Union (AGU), Ch. 3.

Beck, A. E., and Beck, J. M., 1958, On measurements of thermal conductivities of rocks by observations in a divided bar apparatus: Trans. AGU, v. 39, no. 6.

Beck, A. E.; Jaeger, J. C., and Newstead, G. N., 1956, The measurement of the thermal conductivities of rocks by observations in boreholes; Australian J. Physics, v. 9, p. 286-296.

Becker, R. M., and Hooker, V. E., 1967, Some anisotropic considerations in rock stress determinations, U.S. Bur. RI 6965.

Bellier, J., and Debreuille, P., 1977, Three new instruments for measurements in tunnels, in Field Measurements in Rock Mechanics: Proc. Int. Symp., Zurich, 1977, p. 351-357.

Beneez, I., Bodoyni, J., Nagy, B., and Szepesi, I., 1977, Measurement of loads acting on concrete linings, in Field measurements in rock mechanics: Proc. Int. Symp., Zurich, p. 331-344.

Bennett, G. D., and Patten, E. P., Jr., 1962, Constant-head pumping test of a multiaquifer well to determine characteristics of individual aquifers: U.S. Geol. Survey Water Supply Paper 1536-G, p. 181-203.

Benson, R. P., Murphy, D. K., and McCreath, D. R., 1969, Modulus testing of rock at the Churchill Falls underground powerhouse, Labrador, in Determination of the In Situ Modulus of Deformation of Rock: ASTM STP 477, p. 89-116.

Bentall, Ray, 1963, Methods of determining permeability, transmissibility and drawdown: U.S. Geol. Survey Water Supply Paper 1536-I, p. 243-341.

Bentall, Ray (compiler), 1963, Shortcuts and special problems in aquifer tests: U.S. Geol. Survey Water Supply Paper 1545-C, 117 p.

Bernaix, J., 1969, New laboratory methods of studying the mechanical behavior of rocks: Int. J. Rock Mech. Min. Sci., v. 6, no. 1, p. 43-90.

Berry, D. S., and Fairhurst, C., 1966, Influence of rock anisotropy and time-dependent deformation on the stress-relief and high modulus inclusion techniques of in situ stress determination; in Testing Techniques for Rock Mechanics: ASTM STP 402, p. 190-206.

Berry, J. E., 1959, Acoustic velocity in porous media: Trans. AIME, v. 216, p. 262-270.

Bielenstein, H. U., and Barron, K., 1971, In situ stresses: Proc. 7th Canadian Rock Mechanics Symposium, Edmonton,

Bieniawski, Z. T., 1974, Geomechanics classification of rock masses and its application in tunneling: Proc. 3rd Cong. Int. Soc. of Rock Mech., Denver, Colo., v. 2A, p. 27.

Bieniawski, Z. T., Denkhaus, H. G., and Vogler, U. W., 1969, Failure of fractured rock: Int. J. Rock Mech. Min. Sci., v. 6, no. 3, p. 323-341.

____, 1970, Load-deformation behavior of coal after failure: Proc. 2nd Congr. Int. Soc. Rock Mech. Symp., Belgrade, v. I, p. 345-351.

Birch, F., 1966, Compressibility, elastic constants, in Handbook of Physical Constants: Geol. Soc. of Am., Memoir 97, Sec. 7.

Birch, F., and Clark, H., 1940, The thermal conductivity of rocks and its dependence upon temperature: Amer. J. Sci., v. 238, p. 529-558 and 613-635.

Blackwell, J. M., 1954, A transient-flow method for determination of thermal constants of insulating materials in bulk: J. Applied Physics, v. 25, p. 137-144.

____, 1956, The axial flow error in the thermal conductivity probe: Can. J. Physics, v. 34, p 412-417.

Blackwood, R. L., 1977, An instrument to measure the complete stress field in soft rock in a single operation, in Field Measurements in Rock Mechanics: Proc. Int. Symp., Zurich, 1977.

Boord, M., Pratt, H., and Voegele, M., 1979, A heated flatjack test in granite gneiss: Proc. National Waste Terminal Storage Program ONWI, p. 110-112.

Bonnechere, F. J., and Cornet, F. H., 1977, In situ stress measurements with borehole deformation cell, in Field Measurements in Rock Mechanics: Proc. Int. Symp., Zurich, 1977.

Bourke, P. J., Gale, J. E., Hodgekinson, D. P., and Witherspoon, P. A., (in press), tests of porous permeable medium hypothesis for flow over long distances in fractured deep hard rock: Org. Econ. Coop. Div. Workshop, Paris, March 1979.

Bowles, J. E., 1977, Foundation analysis and design: New York, McGraw-Hill Book Company.

Boyer, M. C., 1964, Streamflow measurements, in Chow, V. T., ed., Handbook of Applied Hydrology: New York, McGraw-Hill Book Co.

Bradley, D. B., 1979, Predicting borehole failure near salt domes: Oil and Gas Journal, v. 77 no. 14, 2 April, p. 125-130.

Bradshaw, R. L., Boegly, W. J., and Empson, F. M., 1964, Correlation of conveyence measurements in salt mines with laboratory creep-test data: 6th Symp. Rock Mech., Rolla, Missouri, p. 501-513.

Bradshaw, R. L., et al., 1968, Properties of salt important in radioactive waste disposal: Geol. Soc. Amer., Spec. Paper 88, p. 643-659.

Bredehoeft, J. D., 1965, The drill-stem test: The petroleum industry's deep-well pumping test: Ground Water, v. 3.

Bredehoeft, J. D., and Papadoupulos, S. S., in press, A method for determining the hydraulic properties of tight formations: Water Resources Research.

Breed, C. B., and Hosmer, G. L., 1962, The principles and practice of surveying, v. II: Higher Surveying, 8th Edition, revised by A. J. Bone: New York, John Wiley.

____, 1977, The principles and practice of surveying, V. I-- Elementary Surveying (11th ed.), revised by W. Faig: New York, John Wiley.

Breiner, S., 1973, Applications manual for portable magnetometers: Palo Alto, CA, Geo Metrics.

Bromwell, L. G., Ryan, C. R., and Toth, W. E., 1971, Recording inclinometer for measuring soil movement: Proc. IV Pan Am Conf. on Soil Mech. & Found. Engr., v. 2, p. 333-343.

Brown, E. T., and Hudson, J. A., 1971, The influence of micro-structure on rock fracture on the laboratory scale: Proc. Symp. Rock Fracture, Nancy, 1971.

Brown, R. J. S., and Gamson, B. W., 1960, Nuclear magnetism logging: Trans. AIME, v. 219, p. 199-207.

Brown, R. O., 1979, Fracture identification log use in Cretaceous of N. Louisiana, Mississippi: Oil and Gas Journal, 30 April, p. 350-355.

Bruin, Jack and Hudson, H. E., Jr., 1955, Selected methods for pumping test analysis: Illinois State Water Surv. Rept. of Invent. 25, 54 p.

Brune, J. H. and Allen, C. R., 1967, A micro-earthquake survey of the San Andreas fault system in southern California: Seismological Soc. Am. Bull., v. 57, p. 277-296.

Buchanan, T. J., and Somers, W. P., 1968, Stage measurement at gaging stations: U.S. Geol. Survey Techniques Water-Resources Inv., Book 3, Chap. A7, 28 p.

____, 1969, Discharge measurements at gaging stations: U.S. Geol. Survey Techniques Water-Resources Inv., Book 3, Chap. A8, 65 p.

Bullard, E. C., 1954, The flow of heat through the floor of the Atlantic Ocean: Proc. Royal Soc. London, v. 222, p. 408-429.

Burdin, N. T., 1963, Rock failure under dynamic loading conditions: Soc. Pet. Eng. J., v. 3, p. 1-24.

Burland, J. B., Moore, J.F.A., and Smith, P.D.K., 1972, A simple and precise borehole extensometer: Geotechnique, v. 22, no. 1, p. 174-177.

Butler, D., and Brown, P. L., 1978, Ambient ground-noise measurements and exploration for geothermal resources: Trans. Geothermal Resources Council, v. 2, sec. 1, p. 55-57.

Cagniard, L., 1953, Basic theory of the magneto-telluric method of geophysical prospecting: Geophysics, v. 18, no. 3, p. 605-635.

Cain, P. J., Peng, S. S., and Podnieks, E. R., 1975, Rock fragmentation by high frequency fatigue: U.S. Bureau of Mines, RI 8020.

Cairns, J., and Dickson, K. L., 1973, Biological methods for the assessment of water quality, ASTM Special Technical Publication 528: Philadelphia, American Society for Testing and Materials, 256 p.

California Dept. of Water Resources, 1963, Permeability, coefficients of transmissibility, coefficients of storage, methods of determination and application to ground-water problems - annotated bibliography through 1961: Sacramento, 75 p.

Campbell, M. D., and Lehr, J. H., 1973, Water well technology: New York, McGraw-Hill Book Co., 681 p.

Carlson, R. W., 1958, Manual for the use of stress meters, chain meters and joint meters in mass concrete: Campbell, Calif., Carlson Instrument Co.

Carrillo, N., 1948, Influence of artesian wells in the sinking of Mexico City: Proc. Second Int. Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, v. VII, p. 156-159.

Carter, N. L. and Heard, H. C., 1970, Temperature and rate dependent deformation of halite: Am. J. Sci., v. 269, p. 193-249.

Carter, R. W., and Davidian, J., 1968, General procedure for gaging streams: U.S. Geol. Survey Techniques Water-Resources Investigation, Book 3, Chapter A6, 13 p.

Cartwright, Keros, 1968, Thermal prospecting for ground water: Water Resources Res., v. 4, no. 2, p. 395-403.

Casagrande, A., 1949, Soil mechanics in the design and construction of the Logan Airport: J. of ASCE, v. 36, no. 2, p. 192-221.

Chiu, H. Y., and Collins, W., 1978, A spectroradiometer developed for airborne remote sensing applications: Photogramm. Eng. and Remote Sensing, v. 44, no. 4.

Chrzanowski, A. J., 1970, New techniques in mine orientation surveys: 1st Canadian Symp. on Mine Surveying and Rock Deformation Measurements, 1969, p. 23-46.

Clacy, G., 1968, Geothermal ground-noise amplitude and frequency spectra in New Zealand volcanic region: J. Geophys. Res., v. 73, p. 5377-5383.

Clark, B. R., 1978, Progress in monitoring stress changes near active faults in Southern California, Proc. Conference VII - Stress and Strain Measurements Related to Earthquake Predictions, USGS Open File Report 79-370, p. 84-102.

Clark, H., 1941, The effects of simple compression and wetting on the thermal conductivity of rocks: Trans. Amer. Geophys. Union, Part II, p. 543.

Clark, S. P., Jr., ed., 1966, Handbook of physical constants: New York, Geological Society of America, Memoir 79.

Cluff, L. S., and Slemmons, D. B., 1971, Wasatch Fault Zone--features defined by low-sun angle photography: Utah Geol. Assoc., Publ. 1, p. 61-69.

Coates, D. F., and Gyenge, M., 1965, Plate-load testing on rock for deformation and strength properties: Testing Techniques for Rock Mechanics, ASTM STP 402, p. 19-40.

Cogan, J., 1976, Triaxial creep tests of Opohanga Limestone and Ophir Shale: Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 13, p. 1-10.

____, 1978, An Approach to Creep Behavior in Failed Rocks: 19th Symp. on Rock Mechanics, Stateline, Nevada, p. 400-407.

Colback, P., 1966, An analysis of brittle fracture initiation and propagation in the Brazilian test: Proc. 1st Int. Congr Rock Mech., Lisbon.

Collins, W., 1978, Analysis of airborne spectroradiometric data and the use of LANDSAT data for mapping hydrothermal alteration: Geophysics, v. 43, no. 5, p. 967-987.

Combs, J., and Hadley, D., 1977, Microearthquake investigation of the Mesa geothermal anomaly, Imperial Valley, California: Geophysics, v. 42, no. 1, p. 17-33.

Comes, G., 1965, Contribution à la détermination des caractéristiques méchaniques d'une fondation rocheuse: Travaux.

Conaway, J. G., and Beck, A. E., 1977, Continuous logging of temperature gradients: Tectonophysics, v. 71, p. 1-7.

____, 1977, Fine-scale correlation between temperature gradient logs and lithology: Geophysics, v. 42, no. 7, p. 1401-1410.

Cook, J. C., 1975, Radar transparencies of mine and tunnel rock: Geophysics, v. 40, p. 865-875.

____, 1977, Borehole-radar exploration in a coal seam: Geophysics, v. 42, no. 6, p. 1254-1257.

Cook, N.G.W., and Hojem, J.P.M., 1966, A rigid 50-ton compression and tension testing machine: S. Afr. Mech. Engr., Nov.

Cooper, H. H., Bredehoeft, J. D., and Papadapoulos, I. S., 1967, Response of a finite diameter well to an instantaneous charge of water: Water Resources Research, v. 3, p. 263-269.

Corbett, D. M., 1962, Stream-gaging procedure, a manual describing methods and practices of the Geological Survey: U.S. Geol. Survey Water-Supply Paper 888.

Cording, E. J., Hendron, A. J., and Deere, D. U., 1971, Rock Engineering for Underground Caverns: Proc. Symp. Underground Chambers, Phoenix, p. 567-600.

Cording, E. J., et al, 1975, Methods for geotechnical observations and instrumentation in tunneling: University of Illinois at Urbana - Champaign, NSF Research Grant GI-33644X, UILU-ENG 75 2022.

Cornforth, D. M., 1973, Performance characteristics of slope indicator series 200-B inclinometer, field instrumentation in geotechnical engineering, British Geotechnical Society, p. 126-135.

Crouch, S. L., and Fairhurst, C., 1967, A four-component borehole deformation gauge for the determination of in situ stresses in rock masses: Int. J. Rock Mech. Min. Sci., v. 4, p. 209-217.

Cruden, D. M., 1971a, Single-increment creep experiments on rock under uniaxial compression: Int. J. Rock Mech. Min. Sci., v. 8, p. 127-142.

____, 1971b, The form of the creep law for rock under uniaxial compression: Int. J. Rock Mech. Min. Sci., v. 8, p. 105-126.

Cumming, J. D., and Wicklund, A. P., 1978, *Diamond drill handbook:* Toronto, J. K. Smit and Sons Diamond Products Ltd.

Cummings, B., and Parker, J., 1964, White Pine hydraulic wells: 6th Symp. Rock Mech., Rolla, Missouri, p. 721-748.

Curth, E. A., 1976, Relative pressure changes in coal pillars during extraction--a progress report: U.S. Bureau of Mines RI 6980.

Daeman, J. J. K., 1977, Seismic refraction surveys in a bored tunnel at White Pine Copper Mine: A report to the National Science Foundation - RANN Program on Research Carried Out Under NSF Grant No. APR 72 - 03 01 A02.

Dalrymple, T., and Benson, M. A., 1967, Measurement of peak discharge by the slope-area method: U.S. Geol. Survey Techniques Water-Resources Inv., Book 3, Chapter A2, 12 p.

Dames and Moore, 1978, Boreline rock properties-salt--technical support for GEIS: Radioactive Waste Isolation in Geologic Formations, v. 4, 5/OWI/TM-36/4.

Darnley, A. G., 1970, Airborne gamma-ray spectrometry: Can. Min. Metall. Bull., v. 73, p. 20-29.

Davis, R. E., Foote, F. S., and Kelley, J. W., 1966, Surveying, theory and practice (5th ed.): New York, McGraw-Hill Book Company.

De Chambier, P., 1953, The microlog continuous dipmeter: Geophysics, v. 18, p. 929-951.

Deere, D. O., 1963, Technical description of rock cores for engineering purposes: Rock Mech. and Eng. Geol., v. 18, p. 929.

De la Cruz, R. V., 1978, *Borehole jacking method for elastic property determination in rocks:* Rock Mechanics, v. 10, p. 221-239.

Di Biagio, E., and Myrroll, F., 1972, In situ tests for predicting the air and water permeability of rock masses adjacent to underground openings: *Int. Soc. Rock Mech. and Int. Assoc. Engr. Geol., Proc. of the Symp.* on Percolation through Fissured Salt, Stuttgart.

Dinwiddie, G. A., 1968, Analysis of hydraulic tests in Hot Creek Valley, Nevada: U.S. Geol. Survey Tech. Letter: Central Nevada - 23, prepared *for U.S. Atomic Energy Comm., 63 p.*

Dix, C. H., 1952, Seismic prospecting for oil: New York, Harper.

____, 1955, Seismic velocities from surface measurements: Geophysics, v. 20, no. 1, p. 68-86.

Dobrin, M. B., 1960: Introduction to geophysical prospecting: New York, McGraw-Hill Book Company, 446 p.

Dodds, R. K., 1966, Measurement and analysis of rock physical properties on the Des Project, Iran: Testing Techniques for Rock Mechanics, ASTM STP 402, p. 52-72.

Doll, H. G., 1951, The laterolog, a new resistivity logging method with electrodes using an automatic focusing system: Trans. AIME, v. 192, p. 305-316.

____, 1953, The microlaterolog: Trans. AIME, v. 198, p. 17-32.

Donath, F. A., and Fruth, L. S., 1971, Dependence of strain rate effects on deformation mechanisms and rc . type: J. Geology, v. 79, no. 3, p. 347-371.

Dreyer, H., 1977, Long term measurements in rock mechanics by means of Maihak vibrating wire instrumentation, in Field Methods in Rock Mech., Proc. Int. Symp., Zurich, p. 109-135.

Dreyer, W., 1978, The science of rock mechanics, part 1: Trans. Tech., Aerdermannsdorf, Switzerland.

Dryselius, G., 1965, Design of a measuring cell for the study of rock pressure: IV A Ingenieurswetenschapshandelnievws Meddleland, v. 142, p. 135-144.

Duval, J. S., et al, 1972, Experimental comparison of NaI(Tl) and solid organic scintillation detectors for use in remote sensing of terrestial gamma rays: Geophysics, v. 37, p. 879-888.

Duval, J. S., 1977, High sensitivity gamma-ray spectrometry--state of the art and trial application of factor analysis: Geophysics, v. 42, no. 3, p. 549-559.

Duvall, W. I., 1976, General principles of underground opening design in competent rock: 17th U.S. Symp. on Rock Mechanics, Snowbird, Utah, p. 3A1-1.

Dyck, W., 1972, Radon methods of prospecting in Canada, in uranium prospecting handbook: London Inst. Min. Metall., p. 212-243.

Eagon, H. B., Jr., and Johe, D. E., 1972, Practical solutions for pumping tests in carbonate-rock aquifers: Ground water, v. 10, no. 4, p. 6-13.

Earlougher, R. C., 1977, Advances in well test analysis: Soc. of Petrol. Engrs. Monograph, v. 5, Henry L. Doherty Series, 264 p.

Eastman, 1979, The Eastman borehole surveying system: Houston, Eastman Whipstock, Inc.

Edmonson, W. T., and Winberg, G. G., 1971, A manual on methods for the assessment of secondary productivity in fresh waters: International Biological Programme Handbook No. 17, London, Blackwell Scientific Publications, 358 p.

Edwards, R. N., 1974, The magnetometric resistivity method and its application to the mapping of a fault: Can. J. Earth Sci., v. 11, p. 1136-1156.

Engelder, T., and Sbar, M. L., 1978, A comparison of three strain relaxation techniques, Proc. Conf. VII - Stress and Strain Measurements Related to Earthquake Predictions, Open File Report 79-370, USGS, p. 142-157.

Evans, I., 1964, The expanding bolt seams tester; a theory of tensile breakage: Int. J. Rock Mech. Min. Sci., v. 1, p. 459-474.

Everett, L. G., Schmidt, K. D., Tinlin, R. M., and Todd, D. K., 1976, Monitoring ground-water quality: methods and costs: General Electric Co. - TEMPO, EPA-600/4-76-023, 140 p.

Everling, G. 1964, Comments upon the definition of shear strength: Int. J. Rock Mech. Min. Sci., v. 1, no. 2, p. 145-154.

Fairhurst, C., 1964, On the validity of the Brazilian test for brittle materials: Int. J. Rock Mech. Min. Sci., v. 1, p. 535-546.

____, 1968, Borehole methods of stress determination: Proc. Int. Symp. on Rock Mech., Madrid, p. 273-279.

Farr, J. B., 1979, Seismic resolution as a function of depth: Houston, Western Geophys. Co.

Ferris, J. G., and Knowles, D. B., 1963, Slug test for estimating the coefficient of transmissibility of an aquifer: U.S. Geol. Survey Water-Supply Paper 1516-I, p. 299-304.

Ferris, J. G., Knowles, D. B., Browne, R. H., and Stallman, R. W., 1962, Theory of aquifer tests: U.S. Geol. Survey Water-Supply Paper 1936-E, p. 69-171.

Fileek, H., and Cyrul, T., 1977, Rigid inclusion with high sensitivity, in Field Measurements in Rock Mech.: Proc. Int. Symp., Zurich.

Foote, P., 1964, An expanding bolt seam tester: Int. J. Rock Mech. & Min. Sci., v. 2, p. 255-275.

Franklin, J. A., and Chandra, R., 1972, The Blake durability test: Int. J. Rock Mech. Min. Sci., v. 9, p. 325-341.

Friedman, M., 1972, X-ray analysis of residual elastic strain in quartzite rocks: 10th Symp. Rock Mech., Austin, Texas, 1968, p. 573-595.

Gale, J. E., and Witherspoon, P. A., 1978, An approach to the fracture hydrology at Stripa - preliminary results: Sem. on In-Situ Heating Experiments in Geologic Formations; Org. Econ. Coop. Dev. Ludvika, Sweden.

Gamble, T. D., et al, 1979, Magnetotellurics with a remote magnetic reference: Geophysics, v. 44, no. 1, p. 53-68.

Garber, M. S., and Koopman, F. C., 1968, Methods of measuring water levels in deep wells: U.S. Geol. Survey Techniques of Water Resources Inv. Book 8, Chapter A-1, 23 p.

____, 1968, Methods of measuring water levels in deep wells: U.S. Geol. Survey Techniques of Water-Resources Investigations, Book 8, Chapter A7.

Garotta, R., 1978: Velocities, models applied to seismic interpretation: Oil and Gas Journal, 30 October, p. 126-134.

Gaumer, R. E., Hohnstreeter, G. F., and Vanderschmidt, G. F., 1963, Measurement of thermal radiation properties of solids: NASA Sp.-31, p. 117.

Geidt, W. H., 1957, Principles of heat transfer: Princeton, N.J., D. Van Nostrand and Co., Inc.

Gilliland, J. A., 1972, Principles of ground-water data acquisition: Water Resources Res. v. 8, no. 1, p. 182-187.

Gingrich, J. E. and Fisher, J. C., 1976, Uranium exploration using the track etch method: Presented at IAEA Symp., Vienna, 29 March - 2 April.

Glotzl, F., 1958, A new hydraulic method for remote measurement of mechanical stresses and pressures: Arch. fur technisches Messen, Feb., R21-R23.

Gloyna, E. F., and Reynolds, T. D., 1961, Permeability measurements of rock salt: J. Geophys. Res., v. 66, no. 11, p. 3913-3921.

Goodman, R. E., 1976, Methods of geological engineering in discontinuous rocks: St. Paul, West Publ. Co., 472 p.

Goodman, R. E., Van, T. K., and Heuzé, F. E., 1972, Measurement of rock deformability in boreholes: 10th Symp. Rock Mech., Austin, Texas, 1968, p. 523-556.

Goree, W. S. and Fuller, M., 1976, Magnetometers using RF-driven squids and their application in rock magnetism and paleomagnetism: Rev. Geophys. and Space Phys., v. 14, no. 4, p. 591-608.

Gould, J. P., and Dunnicliff, C. J., 1971, Accuracy of field deformation measurements: Proc. IV Pan Am Conf. on Soil Mech. & Found. Engr., San Juan, v. 1, p. 313-366.

Grant, F. S. and West, G. F., 1965, Interpretation theory in applied geophysics: New York, McGraw-Hill Book Company, 583 p.

Grasty, R. L., 1975, Uranium measurement by airborne gamma-ray spectroscopy: Geophysics v. 40, no. 3, p. 503-519.

Green, G. E., 1973, Principles and performance of two inclinometers for measuring horizontal ground movements, field instrumentation in geotechnical engineering, *British Geotechnical Society*, p. 166-179.

Griggs, D., 1940, Experimental flow of rocks under conditions favoring decrystallization: Geol. Soc. Amer. Bull., v. 56, p. 1001-1022.

Griggs, D. T., 1936, Deformation of rocks under high confining pressures: J. of Geology, v. 44.

Gingarten, A. C., and Witherspoon, P. A., 1972, A method of analyzing pump test data from fractured aquifers: Proceed. Internat. Soc. Rock Mech. and Internat. Assn. Engr. Geol. Symp., Percolation through Fissured Rock, Stuttgart, p. T3-B1 - T3-B9.

Grover, N. C., and Harrington, A. W., 1966, Streamflow: measurements, records and their uses: New York, Dover Publications, Inc., 363 p.

Gupta, H. K., and Rastogi, B. K., 1976, Dams and earthquakes: Amsterdam, Elsevier, 229 p.

Guy, H. P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geol. Survey Techniques Water-Resources Investigations, Book 5, Chapter C1, 58 p.

Guyod, H., and Shane, L. E., 1969, Introduction to acoustical logging: Geophysical Well Logging, v. 1.

Hach Chemical Co., 1977, Drinking water analysis handbook: EPA-Approved *and Hach Methods, Side by Side, 219 p.*

Haimson, B., 1968, Hydraulic fracturing in porous and non-porous rock and its potential for determining in situ stresses at great depth: Ph.D. Thesis, Univ. Minn.

____, 1974, A simple method for estimating in situ stress at great depths: Field Testing and Instrumentation in Rock, ASTM STP 554, Philadelphia, p. 156-182.

____, 1977, Stress measurements using the hydrofracturing technique, in *Field Measurements in Rock Mech.: Proc. Int. Symp., Zurich.*

Haimson, B. C., and Kim, C. M., 1971, Mechanical behavior of rock under cyclic fatigue: Proc. 13th Symp. Rock Mech., Urbana, Ill., p. 845-863.

Halbouty, M. T., 1976, Application of LANDSAT imagery to petroleum and mineral exploration: Amer. Assoc. Pet. Geol. Bulletin, v. 60, no. 5.

Hammer, S., 1950, Density determinations by underground gravity measurements: Geophysics, v. 15, p. 637-652.

Handin, J., Higgs, D. V., and O'Brien, J. K., 1960, Torsion of Yule Marble under confining pressure: Geol. Soc. Amer. Mem. 79, p. 245-274.

Handy, R. L., Pitt, J. M., Engle, L. E., and Klochov, D. E., 1976, Rock borehole shear test: 17th U.S. Symp. on Rock Mech., Snowbird, Utah.

Hansen, E. A., and Harris, A. R., 1974, A ground-water profile sampler: Water Resources Research, v. 10, no. 2, 375 p.

Hantush, M. S., 1956, Analysis of data from pumping tests in leaky aquifers: Trans. Am. Geophys. Union, v. 37, p. 702-714.

____, 1961, Aquifer tests on partially penetrating wells: ASCE Hydraulics Div. J., v. 87, no. HY5, Proc. Paper 2943, p. 171-195.

Hardy, H. R., 1967, Determination of the inelastic parameters of geologic materials from incremental creep experiments: Proc. 3rd Conf. Drilling and Rock Mech., Austin, Texas.

Hardy, H. R. and Chugh, Y. P., 1970, Failure of geologic materials in low-cycle fatigue: Proc. 6th Canadian Rock Mech. Symp., p. 33-47.

Harrill, J. R., 1970, Determining transmissivity from water-level recovery of a step-drawdown test: U.S. Geol. Survey Prof. Paper 700-C, p. 212-213.

Hast, N., 1958, The measurement of rock pressure in mines: Sveriges Geol. Undersokn., Arsbok, Sec. C, 52, no. 3.

____, 1979, Limits of stress measurements in the earth's crust, rock mechanics, v. 11, no. 3, p 143-150.

Hawkes, I., and Bailey, W. V., 1965, Design, develop, fabricate test and demonstrate low costs cylindrical stress gages....: U.S. Bureau of Mines Contract Report 40220050.

Hawkes, I., and Moxon, S., 1965, The measurement of in situ rock stress using the photoelastic biaxial gauge with the core-relief technique: Int. J. Rock Mech. Min. Sci., v. 2, p. 405-419.

Heard, H. C., 1963, The effects of large changes in strain rate in the experimental deformation of Yule marble: J. Geology, v. 71, p. 163-195.

____, 1970, The influence of environment on the inelastic behavior of rocks: Symp. on Engineering with Nuclear Explosives, USAEC, Oakridge, Tenn., v. 1.

____, 1979, Elastic, thermal and permeability behavior of generic respository rocks at in situ conditions, Proc. of the National Waste Terminal Storage Program Information Meeting, Columbus, Ohio, p. 37.

Hedley, D. G. F., 1967, An appraisal of convergence measurements in salt mines: Proc. 4th Can. Rock Mech. Symp., Ottowa, p. 117-135.

____, 1969, Design criteria for multi-wire borehole extensometer systems: 1st Canadian Symp. Mine Surveying and Rock Deformation Measurements, p. 346-377.

Herget, G., 1973, First experiences with the CSIR triaxial strain cell for stress determinations: Int. J. Rock Mech. Min. Sci. & Geo. Abstr., v. 10, p. 509-522.

____, 1973, Variations of rock stress with depth at a Canadian iron mine: Int. J. Rock Mech. Min. Sci., v. 10, p. 37-51.

Heuzé, F. E., and Goodman, R. E., 1970, The design of room and pillar structures in competent jointed rock, example, The Crestmore Mine, Riverside, California: Proc. 2nd Cong. Int. Soc. Rock Mech., Belgrade.

Heuzé, F. E., and Salem, A., 1976, Plate bearing and borehole - jack tests in rock - a finite element analysis, 17th U.S. Symp. Rock Mech., p. 4B8-1 to 4B8-6.

Hickey, J. J., 1972, Important considerations in the process of designing a ground-water data collection program: Water Resources, v. 8, no. 1, p. 178-181.

Hluchanek, J. A., 1973, Radar investigation at the Hockley Salt Dome: M. S. thesis, Texas A and M University.

Hobbs, D. W., 1964, The tensile strength of rocks: Int. J. Rock Mech. Min. Sci., v. 1, p. 385-396.

____, 1965, An assessment of a technique for determining the tensile strength of rock: Brit. J. Appl. Phys., v. 16, p. 259-268.

____, 1970, Stress-strain-time behavior of a number of Coal Measure rocks: Int. J. Rock Mech. Min. Sci., v. 7, no. 2, p. 149-170.

Hoek, E., and Bray, J. W., 1974, Rock slope engineering: London, Inst. of Mining & Metallurgy.

Hoek, E., and Londe, P., 1974, Surface workings in rock: National Acad. Sci., U.S. Nat. Comm. for Rock Mechanics, Advances in Rock Mech., v. 1, part A, p. 523-654.

Hojem, M.P.H., and Cook, N.G.W., 1968, The design and construction of a triaxial and polyaxial cell for testing rock specimens: S. Apr. Mech. Engr., v. 18, no. 2, p. 57-61.

Holister, G. S., 1967, Determination of the mechanical properties of rock in situ: Int. J. Rock Mech. Min. Sci., v. 4, p. 437-448.

Holser, W. T., Brown, R.J.S., Roberts, F. A., Frederiksson, O. A., and Unterberger, R. R., 1972, Radar logging of a salt dome: Geophysics, v. 37, p. 889-906.

Hooker, V. E., and Bickel, P. L., 1971, Overcoming equipment and techniques used in rock stress determination: U.S. Bureau of Mines IC 8618.

Hoskins, E. R., 1966, An investigation of the flatjack method of measuring rock stress: Int. J. Rock Mech. Min. Sci. v. 3, p. 249-264.

____, 1967, An investigation of strain-relief method of measuring rock stress: Int. J. Rock Mech. Min. Sci., v. 4, p. 155-164.

Hoskins, J. R., 1971, A comparative study of selected rock stress instruments: Technical Report NS VI-ISMR-2 Advanced Projects Research Agency, Washington, D.C.

Howell, L. G., Heintz, K. O., and Barry, A., 1966, The development and use of a high precision downhole gravity meter: Geophysics, v. 31, p. 764-772.

Hubbert, M. K., and Willis, D. G., 1957, Mechanics of hydraulic fracturing: Trans. AIME, v. 210, p. 153-168.

Hucka, V., 1965, A rapid method of determining the strength of rock in situ: Int. J. Rock Mech. Min. Sci., v. 2, p. 127-134.

Hudson, J. A., 1969, Tensile strength and the ring test: Int. J. Rock Mech. Min. Sci., v. 6, p. 91-97.

Hudson, J. A., Hardy, M. P., and Fairhurst, C., 1973, The failure of rock beams, Part I - experimental studies: Int. J. Rock Mech. Min. Sci., v. 10, no. 1, p. 69-82.

Hughes Aircraft Co., 1972, Multispectral scanner system for ERTS four band scanner system: NASA document NASA-DR-132758, 133 p.

Hulsing, H., 1967, Measurement of peak discharge at dams by indirect method: U.S. Geological Survey Techniques Water-Resources Investigation, Book 3, Chapter A5, 29 p.

Hult, J., 1963, On the measurement of stresses in solids: Gothenburg, Sweden, Trans. Chalmers Univ. Tech., no. 280.

Hustrulid, W. A., 1976, An analysis of the goodman jack, 17th Symp. Rock Mech., p. 4B10-1 - 4B10-8.

Hustrulid, W. and Hustrulid, A., 1973, The CSM cell - a borehole device for determining the modulus of rigidity of rock: 15th Symp. on Rock Mech., Custer State Park, S. Dakota, p. 181-225.

Hvorslev, J., 1951, Time lag and soil permeability in ground-water observations: Bulletin No. 36, U.S. Army Engineer Waterways Experiment Station.

IAEA, 1974, Emanometers or radon measurement instruments: Vienna, Tech. Report Ser., no. 158.

Ineson, J., 1963, Applications and limitations of pumping tests, hydrogeological significance: J. Inst. Water Engrs., v. 17, p. 200-215.

Interagency Committee on Water Resources, 1941, Methods of analyzing sediment samples: Report No. 4, Federal Interdepartmental Committee, Hydraulic Laboratory of the Iowa Institute of Hydraulic Research, Iowa City, Iowa.

____, 1943, A study of new methods for size analysis of suspended-sediment samples: Report no. 7.

International Society for Rock Mechanics (ISRM), 1972, International Committee on Laboratory Tests: Suggested Methods for Determining Water Content, Porosity, Density, Absorption and Related Properties and Swelling and Slake-Durability Index Properties, Doc. No. 2, 36 p.

____, 1978a, Suggested methods for monitoring rock movements using borehole extensometers: Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 15, no. 6, p. 307-317.

____, 1978b, Suggested methods for determining hardness and abrasiveness of rocks: Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 15, no. 3, p. 89-97.

____, 1979a, Suggested methods for determining the uniaxial compressive strength and deformability of rock materials: Int. J. Rock Mech. Min. Sci. and Geomech. Abstr. v. 16, p. 135-140.

____, 1979b, Suggested methods for determining water content, porosity, density, absorption and related properties and swelling and slak-durability index properties: Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., v. 16, p. 141-156.

Jacob, C. E., 1940, On the flow of water in an elastic artesian aquifer: Trans. Am. Geophys. Union, v. 21, p. 574-586.

Jaeger, J. C., 1956, Conduction of heat in an infinite region bounded internally by a circular cylinder of a perfect conductor: Australian J. Phys., v. 9, p. 167-179.

____, 1965, Application of the theory of heat conduction to geothermal measurements in Lee, W. H. K., ed., Terrestial Heat Flow: Washington, Am. Geophys. Union, ch. 2.

____, 1967, Failure of rocks under tensile conditions: Int. J. Rock, Mech. Min. Sci., v. 4, p. 219-227.

Jaeger, J. C., and Cook, N. G. W., 1964, Theory and application of curved jacks for measurement of stresses: in State of Stress in the Earth's Crust, Amsterdam, Elsevier, p. 381-396.

Jaeger, J. C., and Sass, J. M., 1964, A line source method for measuring thermal conductivity and diffusivity by cylindrical specimens of rock and other poor conductors: Brit. J. Appl. Phys., v. 15, p. 1187-1194.

Janod, A., and Mermin, P., 1954, La mesure de caractéristiques du rocher en place à l'aide du dilatomètre à verin cylindrique: Travaux, p. 610-612.

Jenkins, J. D., 1960, A laboratory and underground study of the bearing capacity of mine floors: Proc. 3rd Int. Conf. Strata Control, Paris, p. 227-235.

John, S. W., 1961, The technique of large scale tests on rock, illustrated by the example of the Kurobe No. 4 concrete dam in Japan: Geol. u. Bauwesen, v. 27, p. 9-19.

Johns, F. B., 1975, Handbook of radiochemical analytical methods, Report No. EPA-6801 4-75-001: Las Vegas, Nev., U.S. Environmental Protection Agency.

Johnson, A. I., 1967, Specific yield--compilation of specific yields for various materials: U.S. Geol. Survey Water-Supply Paper 1662-D, 74 p.

Katz, L. J., 1976, Microtremor analysis of local geological conditions: Bull. Seismol. Soc. Am., v. 61, p. 109-145.

Keller, G. V., and Frischknecht, F. C., 1966, Electrical methods in geophysical prospecting: Oxford, Pergamon Press, p. 527.

King, M. S., 1972, Creep in Model Pillars of Saskatchewan Potash: Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., v. 10, p. 363-371.

King, M. S. and McConnell, B. V., 1973, Fracture evaluation with acoustic log in dry boreholes: Rock Mechanics, p. 273-392.

Knox, R. W., 1956, The Principal tide and current measuring instruments used by the Coast and Geodetic Survey: in Coastal Engineering Instruments, Wiegel, R. L., (Ed.), Council of Wave Research, The Engineering Foundation, p. 227-235.

Koefoed, O., and Biewinga, D. T., 1976, The application of electromagnetic frequency sounding to ground water problems: Geoexploration, v. 14, p. 229-241.

Kokesh, F. p., 1951, Gamma ray logging: Oil & Gas Jour., v. 50, p. 824.

Kovari, K., Amstad, Ch., and Fritz, P., 1977, Integrated measuring techniques for rock pressure determination: in Field Measurements in Rock Mechanics, Proc., Int. Symp., Zurich, p. 289-316.

Kruse, G. H., 1969, Deformability of rock structures, California water project: Determination of the In-Situ Modulus of Deformation of Rock, ASTM STP 477, p. 59-88.

Kruseman, G. P., and de Ridder, N. A., 1970, Analysis and evaluation of pumping test data: Inst. for Land Reclamation and Improvement, Bull. 11, Wageningen, The Netherlands, 200 p.

Kujundic, B., and Stojakovic, M., 1964, A contribution to the experimental investigation of changes of mechanical characteristics of rock masses as a function of depth: Int. Congr. Large Dams, 8th, Edinburgh.

Kunetz, G., 1966, Principles of direct current resistivity prospecting, in Geoexploration Monographs, ser. 1, no. 1: Berlin, Gebr. Borntraeger, 103 p.

____, 1972, Processing and interpretation of magnetoltelluric soundings: Geophysics, v. 37, no. 6, p. 1005-1021.

Lahee, F. H., 1941, Field geology (4th ed.): New York, McGraw-Hill Book Co., Inc.

Lama, R. D., 1966, A comparison of in-situ mechanical properties of coal seams: Colliery Engineering, p. 20-25.

____, 1970, In-situ and laboratory strength of coal: Proc. 12th Symp. Rock Mech., Rolla, Missouri, p. 265-300.

Lama, R. C., and Vutukuri, V. S., 1978, Handbook on mechanical properties of rocks: v. I, II, III and IV, Trans. Tech. Publications, Aedermannsdorf, Switzerland.

____, 1978, Handbook on mechanical properties of rocks: Vol. IV testing techniques and results: Trans. Tech. Publications Series on Rock and Soil Mechanics, v. 3, no. 3, 515 p.

Lambe, T. W., 1951, Soil testing: New York, John Wiley, Ch. II.

____, 1972, The integrated civil engineering project: J. Soil Mechanics and Foundation Division, v. 98, no. SM6, p. 531-556.

LeComte, P., 1965, Creep in rock salt: J. Geology, v. 73, p. 469-484.

Lee, W. H. K., and Lahr, J. C., 1972, HYPO71: A computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes: Menlo Park, USGS Open File Rept., 100 p.

Leeman, E. R., 1964, The CSIR strain gauge cell: CSIR Rept. MEG 417, Pretoria, South Africa.

____, 1964a, The measurement of stress in rocks, part I: The principles of rock stress measurements: J. South Afr. Inst. Min. Metall., v. 65, p. 45-81.

____, 1964b, The measurement of stress in rock, part II: Borehole rock stress measuring instruments: J. South Afr. Inst. Min. Metall., v. 65, p. 82-114.

____, 1964c, The measurement of stress in rock, part III: The results of some rock stress investigations: J. South Afr. Inst. Min. Metall., v. 65, p. 254-284.

____, 1968, The determination of the complete state of stress in rock in a single borehole - laboratory and underground measurements: Int. J. Rock Mech. Min. Sci., v. 5, no. 1, p. 31-36.

____, 1969, The 'doorstopper' and triaxial rock stress measuring equipment developed by CSIR: J. South Afr. Inst. Min. Metall., v. 69, no. 7, p. 305-339.

Leeman, E. R., and Hayes, D. J., 1966, Technique for determining the complete state of stress in rock using a single borehole: Proc. 1st Int. Cong. Rock Mech., Lisbon, v. 2, p. 17-25.

Lehner, F., and Press, F., 1966, A mobile seismograph array: Bull. Seismol. Soc. Am., v. 56, p. 889-898.

Lennox, D. H., 1966, The analysis and application of the step-drawdown test: J. Hydraulics Div., Am. Soc. Civil Engrs., v. 92, no. Hy 6, Proc. Paper no. 4967.

Leroy, L. W., 1951, Subsurface geologic methods: Golden, Colo., Colorado School of Mines.

Leroy, L. W., and Crain, H. M., 1949, Subsurface geologic methods: Golden, Colo., Colorado School of Mines, 826 p.

Le Schack, L. A. and Del Grande, N. K., 1976, A dualwavelength thermal infrared scanner as a potential airborne geophysical exploration tool: Geophysics, v. 41, no. 6, p. 1318-1336.

Leslie, H. D., et al., 1976, Microearthquake location using a maximum likelihood processor: Geophysics, v. 41, no. 5, p. 960-969.

Lin, W., 1978, Measuring the permeability of Eleana Argillite from Area 17, Nevada Test Site, using the transient method: Lawrence Livermore Laboratory UCRL-52604, 11 p.

Lind, O. T., 1974, Handbook of common methods in limnology: St. Louis, C. V. Mosby, 810 p.

Lindner, E. N., and Halpern, J. A., 1978, In-situ stress in North America: Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 15, p. 183-203.

Lindseth, R. O., 1979, Synthetic sonic logs -- a process for stratigraphic interpretation: Geophysics, v. 44, no. 1, p. 3-26.

Lishman, J. R., 1961, Salt bed identification from unfocused resistivity logs: Geophysics, v. 26, p. 320-340.

Logan, J., 1964, Estimating transmissibility from routine production tests of water wells: Ground Water, v. 2, no. 2, p. 35-37.

Lohman, S. W., 1972, Ground-water hydraulics: U.S. Geol. Survey Prof. Paper 708, 70 p.

Lohman, S. W., et al., 1972, Definitions of selected ground-water terms--revisions and conceptual refinements: U.S. Geol. Survey Water-Supply Paper 1988, 21 p.

Lomenick, T. F., and Bradshaw, R. L., 1965, Accelerated deformation of rock salt at elevated temperatures: Nature, v. 207, no. 4993, p. 158-159.

____, 1969, Deformation of rock salt around openings mined for the disposal of radioactive asbestos: Rock Mech., v. 1, p. 5-29.

Lomnitz, C., 1956, Creep measurements in igneous rocks: J. Geol., v. 64, p. 473-479.

Longyear, Inc., 1979, Tropari System: Minneapolis, Longyear, Inc.

Los Alamos Scientific Laboratory (LASL), 1976, LASL hot dry rock geothermal project, July 1, 1975 - June 30, 1976: NTIS LA-6525-PR.

Louis, C., and Pernot, M., 1972, Three-dimensional investigation of flow conditions of Grand Maison damsite: Int. Soc. of Rock Mech., Proc. Symp. on Percolation Through Fissured Rock, Stuttgart, Germany, Paper T4-F, 16 p.

Løvborg, L., et al., 1972, Quantitative interpretation of the gamma-ray spectra from geologic formations: The natural radiation environment II, ERDA, v. 1, p. 155-180.

Lovering, T. S., and Goode, H. D., 1963, Measuring geothermal gradients in drill holes less than 60 feet deep, East Tintic District, Utah: U.S. Geol. Survey Bull. 1172, 48 p.

Lytle, J. D., et al., 1979, General consideration on reservoir instrumentation: The Committee on Measurements of the United States Committee on Large Dams (USCOLD).

Lytle, R. J., Laine, E. F., Lager, D. L., and Davis, D. T., 1979, Cross borehole electromagnetic probing to locate high-contrast anomalies: Geophysics, v. 44, no. 10, p. 1667-1676.

MacKallor, J. A., 1965, Natural gamma aeroradioactivity map of Puerto Rico: U.S. Geol. Survey Geophys. Inv. Map GP-525, 1966.

MacKinley, D. G., and Anderson, W. F., 1975, Determination of the modulus of deformation of a till using a pressuremeter: Ground Engineering, v. 8, no. 6, p. 51-54.

Maini, Y.N.T., and Norishad, J., 1972, Theoretical and field considerations on the determination of in-situ hydraulic parameters in fractured rock: Proc. of the symposium on Percolation through Fissured Salt, Stuttgart, 1972.

Mansur, C. I., 1971, Dewatering and ground-water control for deep excavations: Departments of the Army, the Navy, and the Air Force, Army TM 5-818-5, Navy NAVFAC P-148, Air Force AFM 88-5, Chapter 6, 187 p.

Manzanti, B. B., and Sowers, G. F., 1965, Laboratory testing of rock strength: Proc. Symp. Testing Techniques for Rock Mech., Seattle, Wash., p. 207-227.

Marine, I. W., 1967, The permeability of fractured crystalline rock at the Savannah River plant near Aiken, South Carolina: U.S. Geol. Survey Prof. Paper 575-B, p. B203-B211.

Marino, M. A., and Yeh, W.W.G., 1973, Identification of parameters in finite leaky aquifer system: Am. Soc. Civil Engineers, Jour. Hydraul. Div., v. 99, pt. 2, p. 319-336.

Marr, J. D., and Zagst, E. F., 1967, Exploration horizons from new seismic concepts of CDP and digital processing: Geophysics, v. 32, no. 2, p. 207-224.

Martini, H. J., Durbaum, H., and Giesel, W., 1964, Methods to determine the physical properties of rock: Trans. 8th Int. Cong. Large Dams, Edinburgh, p. 859-869.

Masuda, H., 1975: Seismic refraction analysis for engineering study: Oyo Corp., Tokyo, Tech. Note 10.

Mathews, C. S., and Russell, D. G., 1968, Pr--sure buildup and flow tests in wells: Soc. of Petral. Engrs. Monograph, .ol. 1, Henry L. Dohertz Series, p. 167.

Mayer, A., et al., 1964, Mesure des modules de déformation des massifs rocheux dans les sondages: Trans. 8th Int. Congr. Large Dams, Edinburgh.

Mayne, W. H., 1962, Common reflection point horizontal data stacking techniques: Geophysics, v. 27, no. 6, pt. 2, p. 927-938.

McClain, W. C., 1966, The effect of nonelastic behavior of rocks: Proc. 8th Symp. Rock Mech., Minneapolis, Minn., p. 204-216.

McClain, W. C., and Bradshaw, R. L., 1970, Deformation and stress transference in a salt mine resulting from the application of heat: Proc. 2nd Cong. Int. Soc. Rock Mech., Belgrade, v. 1, p. 559-565.

McCormac, J. C., 1976, Surveying: Englewood Cliffs, N.J., Prentice-Hall.

McVey, J. R., Lewis, S. R., and Guidice, E. L., 1974, Deformation monitoring of underground openings by photographic techniques: U.S. Bureau of Mines, RI 7212.

Meinzer, O. E., 1923, The occurrence of ground water in the United States: U. S. Geol. Survey Water-Supply Paper 489, 321 p.

Meinzer, O. E. and Wenzel, L. K., 1942, Movement of ground water and its relation to head, permeability, and storage, in Meizner, O. E., ed., Hydrology: New York, McGraw Hill Book Co., Inc., p. 444-477.

Menard, L., 1957, Mesures in-situ des propriétés physiques des sols: Annales Ponts Chausses, v. 127, no. 3.

____, 1966, *Rules for the calculation and design of foundation elements* on the basis of pressuremeter investigations of the ground: Denver, Terrametrics.

Moro, J. L., 1960, Uses of the gamma-ray spectrometer in mineral exploration: Geophysics, v. 25, p. 1054-1076.

Merrill, R. H., 1967, Three-component borehole deformation gage for determining the stresses in rock: U.S. Bureau of Mines, RI 7075.

Meyer, T. O. and McVey, J. R., 1974, NX borehole jack modulus determinations in homogeneous, isotropic elastic materials: U.S. Bureau of Mines, RI 7885.

Middleton, W. E. K., and Spilhaus, A. F., 1953, Meteorological instruments (3rd ed.): Toronto, University of Toronto Press, 286 p.

Miller, R. P., 1965, Engineering classification of index properties for intact rock: Ph.D. Thesis, Univ. of Illinois.

Miller, V. C., 1961, Photogeology: New York, McGraw-Hill Book Co., Inc., 248 p.

Mirafuente, N. T., Zurflueh, E. G., and Statton, T., 1974, Improved shear wave measurement technique for better earthquake resistant design: Woodward-Clyde Cons. Geot. Environ. Bull., v. 7, no. 2, p. 25-29.

Misra, A. R., and Murrell, S.A.F., 1965, An experimental study of the effect of temperature and stress on the creep of rocks: Geophys. J. Royal Astronomical Soc., v. 9, p. 509-535.

Misterek, D. L., 1969, Analysis of data from radial jacking tests, in determination of the in-situ modulus of deformation of rock: ASTM STP 477, p. 27-58.

Moffatt, D. L., and Puskar, R. J., 1976, A subsurface electromagnetic pulse radar: Geophysics, v. 41, p. 506-517.

Mogg, J. L., 1969, Step-drawdown test needs critical review: Ground Water, v. 7, no. 1.

Mogi, K., 1971, Effect of the triaxial stress system on the failure of dolomite and limestone: Tectonophysics, v. 11, no. 2, p. 111-127.

Mooney, H. M., 1973, Handbook of engineering geophysics: Minneapolis, Bison Instruments.

Morgan, T. A., Fischer, A. N., and Sturgis, W., 1965, Stress distributions in Westvaco Mine as determined by borehole stress-relief: U.S. Bureau of Mines, RI 6675.

Morris, D. A., and Johnson, A. I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the U.S. Geological Survey 1948-60: U.S. Geol. Survey Water-Supply Paper 1839-D, 42 p.

Mott, N. F., 1952, A theory of work-hardening of metal crystals: Phil. Mag., v. 43, p. 1151-1178, II-A.

Mraz, D., 1978, Theoretical predictions confirmed by in situ rock behavior in deep potash mine: 19th U.S. Symp. Rock Mech., Stateline Nev., p. 468-475.

Musgrave, A. W., ed., 1967, Seismic refraction prospecting: Tulsa, Soc. Explor. Geophys.

Nagata, T., 1961, Rock magnetism: Tokyo, Maruzen, 350 p.

Nakano, H., 1923, Notes on the nature of forces which give rise to earthquake motions: Seismol. Bull., Centre Meteorol. Observ., Japan, v. 1, p. 91-120.

Nelson, K. E., Leudke, E. E., and Bevans, J., 1966, Journal of spacecraft and rockets: v. 3, p. 758.

Nettleton, L. L., 1939, Determination of density for reduction of gravimeter observations: Geophysics v. 4, p. 176-183.

Neuman, S. P., in press, Characterization of aquifer heterogenities - an overview: Proc. symp. on recent trends in Hydrogeology, Lawrence Berkeley Laboratory.

Neuman, S. P., and Witherspoon, P. A., 1972, Field determination of the hydraulic properties of leaky multiple aquifer systems: Water Resources Res., v. 8, no. 5, p. 1284-1298.

Neville, A. M., 1970, Creep of concrete-plain, reinforced and prestressed: Amsterdam, Elsevier.

Nichols, T. C., Abel, J. F., and Lee, F. T., 1968, A solid inclusion borehole probe to determine three-dimensional stress changes at a point in a rock mass: U.S. Geol. Survey Bull. 1258-C.

Noel, G., 1963, Mesure du module d'elasticité en profondeur dans les massifs rocheux: Cellule de mesure de l'Institute Technique du Bâtiment et des Travaux Publics, no. 85, p. 533-540.

Obert, L., 1965, Creep in model pillars: U.S. Bureau of Mines, RI 6703.

Obert, L., Merrill, R. H., and Morgan, T. A., 1962, Borehole deformation gauge for determining the stress in mine rock: U.S. Bureau of Mines, RI 5978.

O'Brien, Maura, et al., 1978, Geotechnical assessment and instrumentation needs for nuclear waste isolation in crystalline and argillaceous rock: Symposium Proc. July 16-20, LBL-7096 Draft, 219 p.

Office of Waste Isolation (OWI), 1976, Natural waste terminal storage program progress report, for period April 1, 1975 to Sept. 30, 1976: Oak Ridge, Tenn., Union Carbide Corp., Report Y/OWI-8.

Oka, Y., and Bain, I., 1970, A means of determining the complete state of stress in a single borehole: Int. J. Rock Mech. Min. Sci., v. 7, p. 503-515.

Oliver, J., et al., 1966, Micro-earthquake activity recorded by portable seismographs of high sensitivity: Bull. Seismol. Soc. Am., v. 56, p. 899-924.

Omega Engineering, Inc., 1979, Temperature measurement handbook, 1979: Stamford, Conn.

Omnes, G., 1975, Microgravity and its applications to civil engineering: Proc. 54th Annual Meeting, Transp. Res. Bd., Washington, D.C.

O'Rourke, J. E., Ridley, A. P., and McConnell, J. R., 1977, Instrumentation and field monitoring of ground cracking: Presented at the International Symposium for Recent Crustal Movements, Stanford University, also Geotech/Envir. Bull., Woodward-Clyde Consultants, p. 17-25.

Pahl, A., 1977, In situ stress measurements by overcoming inductive gages, in Field Measurements in Rock Mechanics: Proc. Int. Symp., Zurich, p. 161-171.

Panek, L. A., 1966, Calculation of the average ground-stress components from measurements of the diametral deformation of a drill hole: ASTM STP 402, Testing Techniques for Rock Mechanics, Seattle, p. 106-132.

____, 1970, Methods and equipment for measuring subsidence: The Northern Ohio Geological Society, Inc., Third Symposium on Salt, v. 2, p. 321-338.

Panek, L. A., Hornsey, E. E., and Lappi, R. L., 1964, Determination of the modulus of rigidity of rock by expanding a cylindrical pressure cell in a drill hole: Proc. 6th Symp. on Rock Mech., Rolla, Missouri.

Panek, L. A., and Stock, J. A., 1964, Development of a rock stress monitoring station based on flat slot of measuring existing rock stress: U.S. Bureau of Mines, RI 6537.

Papadoupulos, I. S., Bredehoeft, J. D., and Cooper, H. H., Jr., 1973, On the analysis of "Slug Test" data: Water Resources Research, v. 9, p. 1087-1089.

Pariseau, W. G., 1978, A note on monitoring stress change in situ, Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 15, p. 161-166.

Parizek, R. R., and Lane, B. E., 1970, Soil-water sampling using pan and deep pressure-vacuum lysimeters: J. of Hydrology, v. 11, p. 1-21.

Parizek, R. R., and Siddiqui, S. H., 1970, Determining the sustained yields of wells in carbonate and fractured aquifers: Ground Water, v. 8, no. 5, p. 12-21.

Patricio, J. G., and Beus, M. J., 1976, Determination of in-situ modulus of deformation in hard rock mines of the Coeur D'Alene district, Idaho: 17th U.S. Symp. on Rock Mech., Snowbird, Utah.

Peacock, K. L., and Treitel, S., 1969, Predictive deconvolution - theory and practice: Geophysics, v. 34, no. 2, p. 155-169.

Perrin, J. R., and Scott, J. J., 1964, The Whole Pine LVDT borehole deformation gage: 6th Symp. Rock Mech., Rolla, Missouri, p. 749-768.

Pettyjohn, W. A., 1967, Evaluation of basic data and a variety of techniques needed in hydrologic systems analysis, in System approach to water quality in the Great Lakes: Proc. 3d. Am. Symp. Water Resources Res., Ohio State Univ. Water Resource Center.

Pickell, J. J., and Heacock, J. G., 1960, Density logging: Geophysics, v. 25, p. 891-904.

Pirson, S. J., 1958, Oil reservoir engineering (2nd ed.): New York, McGraw-Hill Book Company, Inc.

Pontecorvo, B., 1941, Neutron well logging: Oil & Gas Journal, v. 40, 32 p.

Potts, E. L. J., 1957, Underground instrumentation: Colo. School of Mines Quarterly, v. 52, p 135-182.

____, 1964, An investigation into the design of room and pillar workings in rock salt: The Mining Engineer, Oct., p. 27-44.

Potts, E.L.J., Dunham, R. K., Maconochie, B. E., and Reid, A. G., 1976, Design and installation of ground instrumentation for the Channel Tunnel in Tunnelling '76: Location Inst. Min. Metall.

Potts, E.L.J., Szeki, J., and Rowley, N. A., 1974, Report to Mott, Hay and Anderson on in-situ stress determinations carried out in the experimental tunnel at Sangatte, France, for R.T.Z.

Powell, R. W., 1957, Experiments using a simple thermal comparator for measurements of thermal conductivity, surface roughness and thickness of foils or of surface deposits: J. Sci. Instr., v. 34, p. 485-492.

Price, D. G. and Knill, J. L., 1966, A study of the tensile strength of isotropic rocks: Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, v. I, p. 439-442.

Price, N. J., 1964, A study of the time-chain behavior of coal-measure rocks: Int. J. Rock Mech. Min. Sci., v. 1, p. 277-303.

Prothero, W. A., and Brune, J. N., 1971, A suitcase seismic recording system: Bull. Seismol. Soc. Am., v. 61, p. 1849-1853.

Protodyakonov, M. M., 1969, Methods of determining the shear strength of rocks in Protodyakonov, M. M., Koifmann, M. I., et al., Mechanical Properties of Rocks, p. 15-27.

Rantz, S. E. and Herschy, R., et al., in press, Stream gaging manual (tentative title): Geneva, Secretariat of the World Meteorological Organization.

Rantz, S. E., et al., in press, Measurement of stage - V. 1; Computation of discharge - V. 2: U.S. Geol. Survey Water Supply Paper 2200.

Ray, R. G., 1960, Aerial photographs in geologic interpretation and mapping: U.S. Geol. Survey Prof. Paper 373.

Reeves, R. G. (ed.), 1975, Manual of remote sensing: Amer. Soc. of Photogrammetry, Keuffel and Esser Co., 2144 p.

Riley, P. B., Goodman, R. E., and Nolting, R. M., 1977, Stress measurement by overcoring cast photoelastic inclusions: 18th U.S. Symp. Rock Mech., Keystone, Colo., p. 4C 4-1.

Ritter, J. R., and Helley, E. J., 1969, Optical method for determining particle sizes of coarse sediment: U.S. Geological Survey Techniques of Water-Resource Investigation, book 5, ch. C3, 33 p.

Roberts, A., 1968, Measurement of strain and stress in rock masses in Rock Mechanics in Engineering Practice: New York, John Wiley and Sons, ch. 5, p. 125-202.

Robertson, C. E., 1963, Well data for water well yield map: Missouri Geol. Survey and Water Resources, 23 p.

Robertson, E. C., 1963, Viscoelasticity of rocks: Proc. Int. Conf. State of Stress in the Earth's Crust, Santa Monica, Calif., p. 180-224.

Rocha, M., 1966, Rock mechanics in Portugal: Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, v. 3, p. 121-132.

___, 1968, New technique for determination of the deformability and state of stress in rock masses: Int. Symp. Rock Mech., Madrid, p. 289-302.

___, 1969, New techniques in deformability testing of in-situ rock masses: Determination of the In Situ Modulus of Deformation of Rock, ASTM STP 477.

___, 1973, A method of obtaining integral samples of rock masses: Bull. Assoc. Engineering Geologists, v. 10, no. 1, p. 77-82.

Rocha, M., and Silverio, A., 1969, A new method for the complete determination of the state of stress in rock masses: Geotechnique, v. 19, no. 1, p. 116-132.

Rogiers, J. C., 1975, The development and evaluation of a field method for in-situ stress determination using hydraulic fracturing: Ph.D. Thesis, Univ. of Minn.

Rorabaugh, M. I., 1953, Graphical and theoretical analyses of step-drawdown test of artesian wells: Proc. ASCE, v. 79, sep. 362, 23 p.

Rowan, L. C., et al., 1974, Discrimination of rock types and detection of hydrothermally altered areas in south-central Nevada by the use of computer-enhanced ERTS images: U.S. Geol. Survey Prof. Paper 883, 35 p.

Roy, A., and Dhar, R. L., 1971, Radius of investigation in d.c. well resistivity logging: Geophysics, v. 36, p. 754-760(T).

Royea, M. J., 1970, Rock stress measurement at the Sullivan Mine: Proc. 5th Canadian Rock Mech. Symp., p. 59-74.

Rummel, R. and Fairhurst, C., 1970, Determination of the postfailure behavior of brittle rock using a servo-controlled testing machine: Rock Mechanics, v. 2, p. 189-204.

Sabins, F. F., Jr., 1978, Remote sensing principles and interpretation: San Francisco, W. H. Freeman, 426 p.

Salt, D. J., and Clark, A. R., 1951, The investigation of earth resistivities in the vicinity of a diamond drill hole: Geophysics, v. 16, p. 659-665.

Sass, J. H., 1961, In-situ measurement of rock conductivities, M. Sc. Thesis, Univ. Western Ontario, London, Ontario, 1961.

Sauer, G., and Sharma, P., 1977, A system for stress measurement in constructions in rock: Field Measurements in Rock Mechanics, Proc. Int. Symp., Zurich, p. 317-329.

Savit, C. H., 1978, Computer contouring method gives geologic sections from seismic data: Oil and Gas Journal, 30 October, p. 86-90.

Schlumberger Limited, 1972, Log interpretation, v. 1 -- principles: New York, Schlumberger.

Schmidt, B., and Dunnicliff, C. J., 1974, Construction monitoring of soft-ground rapid transit tunnels: a definition of needs and potential development: UMTA Report No. MA-06-0025-74-13; also NTIS Report Nos. PB-241536 and PB-241537.

Schmoker, J. W., 1978, Accuracy of borehole gravity data: Geophysics, v. 43, no. 3, p. 538-542.

Science Applications, Inc., 1978, Technical support for GEIS: radioactive waste isolation in geologic formations, v. 19, thermal analysis: prepared for Office of Waste Isolation, Union Carbide Corporation, Oak Ridge, Tenn., NTIS Y/OWI/TM-36/19.

Scott, J. H., Carroll, R. D., Robinsion, C. S., and Lee, F. T., 1974, Engineering geologic, hydrologic, and rock mechanics investigations of the Straight Creek tunnel site and pilot bore, Colorado: U.S. Geol. Survey Prof. Paper 815, p. 51-77.

Sellers, J. B., 1970, The measurement of rock stress changes using hydraulic borehole gages: Int. J. Rock Mech. Min. Sci., v. 7, p. 423-435.

____, 1974, Measurement of in-situ shear strength using torsional shear method: Proc. Symp. Field Testing and Instrumentation, ASTM STP 544, p. 147-155.

Sellers, W. D., 1965, Physical climatology: Chicago, The University of Chicago Press, 272 p.

Serafim, J. L., and Guerreiro, M., 1966, In-situ tests for the study of rock foundations of concrete dams: Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, v. II, p. 549-556.

Serafim, J. L., and Lopes, J.J.B., 1962, In situ tests and triaxial tests on foundation rocks of concrete dams: Lisbon, Lab. Nac. de Eng. Civil, Tech. Paper no. 190.

Serata, S., 1968, Application of continuum mechanics to design in deep potash mines in Canada: Int. J. Rock Mech. & Min. Sci., v. 5, no. 4, p. 293-314.

Serata, S., Sukurai, S., and Adachi, T., 1972, Theory of aggregate rock behavior based on absolute three-dimensional testing (ATT) of rock salt: Proc. 10th Symp. on Rock Mechanics, Austin, Texas, 1968, p. 431-473.

Serdengecti, S., and Boozer, G. D., 1961, The effects of strain rate and temperature on the behavior of rocks subjected to triaxial compression: Proc. 4th Symp. Rock Mech., University Park, PA, p. 83-97.

Sharma, R. P., and Raphael, J., 1979, Seismic considerations: General Considerations on Reservoir Instrumentation, Measurements Committee, USCOLD, Section II.

Sherwood, D. T. and Currey, B., 1973, Experience in using electrical tiltmeters, field instrumentation in geotechnical engineeirng, British Geotechnical Society, p. 382-395.

Shuter, E., and Johnson, A. I., 1961, Evaluation of equipment for measurement of water level in wells of small diameter: U.S. Geol. Survey, Circular 453.

Sill, C. W. and Willis, C. P., 1962, Fluorometric determination of submicrogram quantities of thorium: Anal. Chem., v. 34, no. 8, p. 954-964.

____, 1964, Precipitation of submicrogram quantities of thorium by barium sulphate and application to fluorometric determination of thorium in mineralogical and biological samples: Anal. Chem., v. 36, no. 3, p. 622-630.

Simon, A. L., 1976, Practical hydraulics: New York, John Wiley and Sons, Inc., 306 p.

Skibitzke, H. E., 1963, Determination of the coefficient of transmissibility from measurements of residual drawdown in a bailed well: U.S. Geol. Survey Water-Supply Paper 1536-I, p. 293-298.

Skilton, D., 1971, Behavior of rigid inclusion stressmeters in viscoelastic rock: J. Int. Soc. Rock Mech. Min. Sci., v. 8, p. 283-289.

Slack, K. V., Averett, R. C., Greeson, P. E., and Lipscomb, R. G., 1973, Methods for collection and analysis of aquatic biological and microbiological samples: Techniques of Water-Resources Investigations of the U.S. Geol. Survey, ch. A4, book 5, 165 p.

Slemmons, D. B., 1969, New methods of studying regional seismicity and surface faulting: Geoscience, v. 10, art. 1, p. 92-103, and EOS, Trans. Amer. Geophys. Union, v. 50, p. 397-398.

Slope Indicator Company (SINCO), 1979, Borehole extensometers and inclinometers: Seattle, Washington.

Smart, B. G. D., Singh, R. M., and Issac, A. K., 1978, A borehole instrument system for monitoring shake displacement in three dimensions: Int. Jour. Rock Mech. Min. Sci. & Geomech. Abstr. v. 15, p. 77-85.

Smith, P. D. K. and Burland, J. B., 1976, Performance of high precision multipoint borehole extensometer in soft rock: Can. Geotech. J., v. 13, p. 172-176.

Snow, D. T., 1968, Rock fracture spacing, openings and porosities: J. Soil Mech. and Foundation Eng., v. 94, p. 73-91.

Sokol, D., 1966, Interpretation of short term water level fluctuations in the Moscow Basin, Latah County, Idaho: Idaho Bureau of Mines and Geology, Pamphlet 137.

Staley, W. W., 1964, Introduction to mine surveying: Palo Alto, Stanford Univ. Press.

Stallman, R. W., 1971, Aquifer test design, observation and data analysis: Techniques of Water-Resources Investigations of the U. S. Geol. Survey, book 3, ch. B1, 26 p.

Stans, M. H., White, R. M., and Cressman, G. P., 1970, Substation observations: *Weather Bureau, Observing Handbook No. 2, Supersedes Circular B*, 1st ed., Data Acquisition Division Office of Meteorological Operations, Silver Spring, Md.

Starfield, A. M. and McClain, 1973, Project salt vault: a case study in rock mechanics: Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 10, p. 641-657.

Stauder, W., 1962, The focal mechanism of earthquakes: Advances in Geophysics, v. 9, p. 1-76.

Stearns, N. D., 1928, Laboratory tests on physical properties of water-bearing materials: U.S. Geol. Survey Water-Supply Paper 596F, p. 121-176.

Stears, J. H., 1965, Evaluation of penetrometer for estimating roof bolt anchorage: U.S. Bureau of Mines RI 6646.

Stewart, R. D., and Unterberger, R. R., 197?, Seeing through rock salt with radar: Geophysics, v. 41, p. 123-132.

Stipp, D. W., 1962, Trilateration adjustment: Surveying and Mapping, v. 22, no. 4, p. 575-580.

Stowe, R. L., and Ainsworth, D. L., 1972, Effect of rate of loading on strength and Young's modulus of elasticity of rock: Basic and Applied Rock Mechanics, Proc. 10th Symp. on Rock Mech., Austin, Texas, 1968, p. 3-34.

Swolfs, H. S., and Brechtel, C. E., 1977, The direct measurement of long-term stress variations in rock: 18th U.S. Symp. Rock Mech., Keystone, Colo., p. 4C5-1.

Talobre, I. A., 1961, Dez Dam foundation tests analysis: New York, Development Resources Corp.

___, 1964, La mesure in-situ des propriétés méchaniques des roches et la sécurité des barrages de grande hauteur: Proc. 8th Cong. on Large Dams, v. 20, No. 28, p. 533-540.

Talvitie, N. A., and Garcia, W. A., 1965, Radiochemical determination of lead-210 after solvent extraction as iodide and dithizonate: Anal. Chem., v. 37, no. 7, p. 851-854.

Tanner, A. B., 1964, Radon migration in the ground: a review, in The natural radiation environment: Chicago, Univ. of Chicago Press, p. 161-190.

Teledyne Geotech, 1972, Geothermal noise survey of the East Mesa area, Imperial Valley, California: Garland, Texas, Tech. Rept. no. 72-19, 18 p.

Telemac International, Inc., 1979, Tiltmeters, inclinometers: Montreal, Canada.

Telford, W. M., et al., 1976, Applied geophysics: Cambridge, Cambridge Univ. Press.

Tencelin, M. E., 1951, Measurement of earth pressures in the iron mines of Lorraine: Int. Conf. Rock Pressures Support at the Working Face, Liège, p. 158-175.

Terrametrics, 1979, Extensometers, convergence gages, tiltmeters, inclinometers: Golden, Colorado.

Terra Technology Corp., 1979, Inclinometers: Seattle, Washington.

Terzaghi, K., 1962, Stability of steep slopes on hard, unweathered rock: Geotechnique, v. 12, no. 4, p. 251-270; also Harvard Soil Mechanics Series no. 69.

Terzaghi, K., and Peck, R. B., 1967, Soil mechanics in engineering practice (2nd. ed.): New York, John Wiley.

Tesch, W. J., Jr., 1976, Automated borehole surveying system for steeply inclined cased boreholes: U.S. Bureau of Mines, RI 8176.

Testlab Corp., 1967, Geoprobe: Chicago, Ill.

Thatcher, L. L., Janzer, V. J., and Edwards, K. W., 1977, Methods for determination of radioactive substances in water and fluvial sediments: U.S. Geological Survey, Techniques of Water-Resources Investigation, book 5, ch. A-5, 95 p.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Trans. Am. Geophys. Union, v. 14, pt. 2, p. 519-524.

Thiem, G., 1906, Hydrologische Methoder: Leipzig, J. M. Gebhardt, 56 p.

Todd, D. K., Tinlin, R. M., Schmidt, K. D., and Everett, L. G., 1976, Monitoring ground water quality: Monitoring methodology: General Electric Co.-TEMPO, EPA-60014-76-026, 154 p.

Trantina, J. A., and Cluff, L. S., 1963, NX borehole camera: American Society for Testing and Materials, Special Technical Publication no. 351.

U.S. Bureau of Reclamation, 1977, Ground water manual: Washington, D.C., U.S. Govt. Printing Office, 480 p.

____, 1967, Water measurement manual (2nd ed.): 32 p.

U.S. Bureau Environmental Protection Agency (EPA), 1974, Methods for chemical analysis of water and wastes: Cincinnati Environmental Monitoring and Support Laboratory, EPA-625-/6-74-003a.

U.S. Environmental Protection Agency, 1976, Manual of water well construction practices: Office of Water Supply, EPA-570-/9-75-001.

U.S. Government, 1977, National handbook of recommended methods for water-data acquisition: prepared under the sponsorship of the Office of Water-Data Coordination, U.S. Geological Survey, Reston, VA.

U.S. Federal Interagency Work Group on Designation of Standards for Water Data Acquisition, 1972, Recommended methods for water-data acquisition, preliminary report: Government Printing Office, Washington, D.C., 415 p.

____, (Kisselman, H. E., ed.), 1974, Earth manual (2nd. ed.): p. 243-253, 650-699.

____, 1977, Ground water manual (1st ed.): 480 p.

Van Heagen, P. P., and Maxwell, A. E., 1959, The measurement of thermal conductivity of deep sea sediments by a needle probe method: J. Geophys. Res., v. 64, p. 1557-1563.

Van Nostrand, R. G., and Cook, K. L., 1966, Interpretation of resistivity data: U.S. Geol. Survey Prof. Paper 499, 310 p.

Van Schalkwyk, A., 1976, Rock engineering testing in exploratory boreholes, Proc. Symp. in Exploration for Rock Engineering, Johannesburg, p. 37-55.

Vanyan, L. L., et al., 1967, Electromagnetic depth soundings: New York, Plenum Press, 312 p.

Viksne, A., et al., 1969, SLR reconnaissance of Panama: Geophysics, v. 34, no. 1, p. 54-64.

Vincent, R. K., 1975, The potential of thermal infrared multispectral scanners in geologic remote sensing: Proc. IEEE, v. 63, p. 137-147.

Voight, B., 1967, Determination of the virgin state of stress in the vicinity of a borehole from measurements of a partial inelastic strain tensor in drill cores: Rock Mechanics, v. 6, p. 201-215.

Vollenweider, R. A., 1974, A manual on methods for measuring primary production in aquatic environments (2nd ed.): International Biological Programme, Handbook no. 12, Blackwell Scientific Publications, London, 225 p.

Voloshin, V., Nixon, D., and Timberlake, L., 1968, Oriented core: a new technique in engineering geology: Bull. Assoc. Engineering Geologists, v. V, no. 1.

Von Herzen, R. P., and Maxwell, A. E., 1959, The measurement of thermal conductivity of deep sea sediments by a needle probe method: J. of Geophys. Res., v. 4, p. 1557-1563.

Von Herzen, R. P., and Uyeda, S., 1963, Heat flow through the eastern Pacific floor: J. Geophys. Res., v. 68, no. 14, p. 4219-4250.

Wagner, H. and Schümann, 1971, The stamp-load bearing strength of rock, an experimental and theoretical investigation: Rock Mechanics, v. 3, p. 185-207.

Walker, P. M., and Trexler, D. T., 1977, Low sun-angle photography: Photogrammetric Engineering and Remote Sensing, v. XLIII, no. 4.

Wallace, G. R., Slebir, E. J., and Anderson, F. A., 1972, Radial jacking test for arch dams: Proc. 10th Symp. on Rock Mechanics, Austin, Texas, 1968.

____, 1969, In-situ methods for determining deformation modulus used by the Bureau of Reclamation: Determination of the In Situ Modulus of Deformation of Rock: ASTM STP 477, p. 3-26.

Walsh, J. B., and Decker, E. R., 1966, Effect of pressure and saturating liquid on the thermal conductivity of compact rock: J. Geophys. Res., v. 71, no. 12, p. 3053.

Walton, W. C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois Water Survey Bull. 49, 81 p.

____, 1970, Ground water resource evaluation: New York, McGraw-Hill Book Company, Inc., 664 p.

Wang, J., Tsang, C. F., Narisimhan, T. N., and Witherspoon, P. A., 1977, Transient flow in tight fractures: Proc. 1st Invitational Well Testing Symposium, Lawrence Berkeley Laboratory.

Warren, R. K., 1977, Recent advances in uranium exploration with electronic alpha cups: Geophysics, v. 42, no. 5, p. 982-989.

Wawersik, W. R., 1968, Experimental study of the fundamental mechanisms of rock failure in static uniaxial and triaxial compression and uniaxial tension: Ph.D. Thesis, Univ. of Minn.

____, 1974, Time dependent behavior of rock in compression: Proc. 3rd. Cong. Int. Soc. Rock Mech., Denver, Colo., p. 357-363.

Wawersik, W. R., and Brown, W. J., 1971, Creep fracture in rock in uniaxial compression: Proc. 3rd Cong. Int. Soc. Rock Mech., Denver, Colo.

Wawersik, W. R., and Fairhurst, C., 1970, A study of brittle rock fracture in laboratory compression experiments: Int. J. Rock Mech. Min. Sci., v. 7, p. 561-575.

Weber, C. I. (ed.), 1973, Biological field and laboratory methods for measuring the quality of surface waters and effluents: EPA-670-4-73-001, Environmental Protection Agency, Cincinnati, 186 p.

Weeks, J. B., et al., 1974, Simulated effects of oil-shale development on the hydrology of Piceance Basin, Colorado: U.S. Geol. Survey Prof. Paper 908, 84 p.

Welch, P. S., 1948, Limnological methods: New York, McGraw-Hill Book Company, Inc., 381 p.

Weller, C. E., 1974, Seismic exploration method: U.S. Patent No. 3,812,457.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods, (and) with section on direct laboratory methods and bibliography on permeability and laminar flow, by V. C. Fishel: U.S. Geol. Survey Water-Supply Paper 887, 192 p.

Westphal, W. H., and Lange, A. L., 1966, Local seismic monitoring: Final Tech. Rept. SRI Proj. PHU-5043 Advanced Research Projects Agency, Washington, 242 p., 1967, Local seismic monitoring-Fairview Peak area, Nevada, Bull. Seismol. Soc. Am., v. 57, p. 1279.

Widco, (date unknown), Operators manual for Widco logger: Widco Division, Gearhart-Owen Industries, Inc., Fort Worth, Texas.

Widess, M. B., 1973, How thin is a thin bed?: Geophysics, v. 38, no. 6, p. 1176-1180.

Wiid, B. L., 1970, The influence of moisture on the pre-rupture fracturing of two rock types: Proc. 2nd Cong. Int. Soc. Rock Mech. Min. Sci., Belgrade, v. 9, no. 2, p. 249-260.

Wiles, C. J., 1979, Mini-Sosie: new concept in high resolution seismic surveys: Oil and Gas Journal, v. 77, no. 11, 12 March, p. 94-97.

Wilson, A. H., 1961, A laboratory investigation of a high modulus borehole plug gage for measurement of rock stress: Proc. Symp. Rock Mech. 4th, Bull. Mineral Experimental Sta., Penn. State Univ., no. 76, p. 185-195.

Wilson, C. R., Doe, T. W., Long, J.C.S., and Witherspoon, P. A., in preparation, Permeability characterization of nearly impermeable rock masses for nuclear waste repository siting: Lawrence Berkeley Laboratory, Univ. of Calif., Berkeley, Calif. (draft report, 6 March 1979).

Wilson, Jr., F. F., 1968, Fluorometric procedures for dye tracing: U.S. Geol. Survey Techniques of Water-Resources Inv., book 3, ch. A12, 31 p.

Wilson, S. D., and Hancock, C. W., 1965, Instrumentation for movements within rock-fill dams: Instruments and Apparatus for Soil and Rock Mechanics: ASTM, STP 392, p. 115-130.

Winter, T. C., 1972, An approach to the design of statewide or regional ground-water information systems: Water Resources Res., v. 8, no. 1, p. 222-230.

Winterkorn, H. F., and Fang, H., 1975, Foundation engineering handbook: New York, Von Nostrand Rheinhold Company.

Witherspoon, P. A., 1977, Summary review of workshop on movement of fluids in largely impermeable rocks: Report from seminars held at the University of Texas (Austin) by Office of Waste Isolation (OWI), Union Carbide Corp. NTIS Y/OWI/SUB-771 14223.

Wood, W. W., 1973, A technique using porous cups for water sampling at any depth in the unsaturated zone: Water Resources Research, v. 9, no. 2, p. 486-488.

World Meteoroglogical Organization, (WMO), 1974, Guide to hydrological practices (3rd ed.): Geneva, Secretariat of the WMO, WMO-No. 168.

Worotnicki, G., Enever, J. R., and Spathis, A., 1976, A pressiometer for determination of modulus of rock in-situ: Proc. In-situ Testing of Rock Parameters, Victorian Geomech. Soc., Melbourne, Australia.

Worthington, P. F., and Griffiths, D. A., 1975, The application of geophysical methods in the exploration and development of sandstone aquifers: Quart. J. Eng. Geol., v. 8, p. 73-102.

Wuerker, R. G., 1959, Influence of stress rate and other factors on the strength and elastic properties of rocks: Quarterly of the Colorado School of Mines, v. 54, no. 3.

____, 1959, The shear strength of rocks: Mining Eng., v. 11, no. 10.

Wyllie, M. J. R., 1949, Statistical study of accuracy of some connate-water resistivity determinations made from self-potential log data: Am. Assoc. Petroleum Geologists Bull., v. 33, p. 1892-1900.

Wyllie, M.J.R., Gregory, A. R., and Gardner, G. H. F., 1958, An experimental investigation of factors affecting elastic wave velocities in porous media: Geophysics, v. 23, p 459-493.

Yarger, H. L., et al, 1978, Diurnal drift removal from aeromagnetic data using least squares. Geophysics, v. 43, no. 6, p. 1148-1156.

Zamanek, J., et al., 1970, Formation evaluation by inspection with the borehole televiewer: Geophysics, v. 35, p. 254-269.

Zones, C. P., 1957, Changes in hydraulic conditions in the Dixie Valley areas, Nevada, after the earthquake of December 16, 1954: Seismological Soc. Am. Bull., v. 47, p. 387-396.

Ziegler, T. W., 1976, Determination of rock mass permeability: U.S. Army Engineer Waterways Experiment Station Technical Report S-76-2, 87 p.

Zienkiewicz, O. C., and Stagg, K. G., 1967, Cable methods of in-situ rock testing: Int. J. Rock Mech. Min. Sci., v. 4, p. 273-300.

Zierfuss, H., 1963, An apparatus for the rapid determination of the heat conductivity of poor conductors: J. Sci. Instr., v. 40, p. 69-71.

Zimmer, P. W., 1963, Orientation of small diameter drill core: Quarterly of the Colorado School of Mines, v. 58, no. 4, p. 67-82.

Zohdy, A. A. E., et al., 1974, Application of surface geophysics to groundwater investigations: Techniques of Water-Resources Investigations of the U.S. Geol. Survey, ch. D1, book 2, Washington, 116 p.

Zones, C. P., 1957, Changes in hydraulic conditions in the Dixie Valley areas, Nevada, after the earthquake of December 16, 1954: Seismological Soc. Am. Bull, v. 47, p. 387-396.

Zurflueh, E. G., 1968, High speed processing of aeromagnetic survey data (abstract), Trans. Amer. Geophys. Union, v. 49, p. 671.

APPENDIX A
GEOPHYSICAL MEASUREMENTS:
INSTRUMENTATION AND SURVEY TECHNIQUES

A.1 MAGNETIC MEASUREMENTS

A. Instrumentation

During the last ten years, emphasis has shifted to proton precession magnetometers and optical pump magnetometers, and away from fluxgate magnetometers and field balances which were previously used in aeromagnetic and ground-magnetic surveys, respectively.

The modern magnetometers are based upon principles of quantum mechanics. Proton precession magnetometers, probably the most widely used instruments today, utilize the nuclear magnetic resonance of protons. The resonance frequency, or frequency of proton precession, is directly proportional to the magnetic field surrounding the sample. Measurement of this frequency provides, therefore, a measure of the total intensity of the magnetic field.

The magnetometer first polarizes the protons in a direction normal to the earth's field, then removes the polarizing field, allowing the protons to precess freely in the earth's field. The protons precess at an angular velocity ω, proportional to the magnetic field strength H, according to the relationship $\omega = \gamma_p H$, where the constant γ_p is the gyromagnetic ratio (the ratio of the proton's magnetic moment to its spin angular momentum). The signal from the precession of the protons is detected by means of a coil coupled to the proton source; a voltage is induced that varies at the precession frequency. The field strength can, therefore, be determined from the equation

$$H = \omega/\gamma_p = 2\pi f/\gamma_p$$

Since the earth's field strength is approximately 5 x 10^4 nT, and the term $2\pi/\gamma_p$ equals about 23.5 nT/Hz, the frequency measuring device must operate in the audio range at about 2130 Hz. The value of γ_p is known to an accuracy of 0.25 x 10^{-4}, and it is possible to determine to the same accuracy the strength of the magnetic field. Proton magnetometers have a sensitivity of approximately 1 to 0.1 nT.

The measurement of total field intensity is absolute and independent of the orientation of the sensing unit. Only the amplitude of the signal varies with orientation and these amplitude effects can be eliminated by using two perpendicular sensors or toroidal sensors that are omnidirectional. The older fluxgate instruments depend on servo-alignment of the measuring unit. They are, therefore, subject to alignment errors.

Higher sensitivity is provided by optical pump magnetometers using Zeeman effects in cesium (Cs) or rubidium (Rb) vapor. Cesium-133 yields a frequency of 3.50 Hz/nT.

Optical pumping (similar to laser applications) amplifies the Zeeman effect to provide a very sensitive measurement. In addition, the amplitude of the signal measured is independent of the frequency so that the sensitivity of the Cs-vapor magnetometer is independent of the field being measured. The amplitude, as in the proton magnetometer, is dependent on the direction of the field.

Rubidium vapor has an even higher frequency than cesium, but it also has an asymmetric resonance curve, so that present use favors Cs-vapor magnetometers. Sensitivity of these instruments ranges from 0.01 to 0.001 nT.

Even higher sensitivities can be achieved with superconducting quantum interference device (SQUID) magnetometers using electron pair tunneling effects in Josephson junctions (Goree and Fuller, 1976). These devices, having a senstivity of 0.0001 nT or better and excellent high-frequency response, would be especially advantageous for gradient measurements. However, additional logistical problems are introduced by the fact that they have to be operated at cryogenic temperatures.

B. Survey Techniques

1. Aeromagnetic Surveys - In aerial surveys, navigational errors introduce a second source of uncertainty, in addition to time variations of the magnetic field. Aeromagnetic surveys, therefore, have to be designed to permit elimination of both sources of errors.

Time variations of the field can be eliminated or attenuated by using a base station on the ground, by a flight line pattern with loops and tie lines, or by computer processing and statistical analysis of line intersections (Zurflueh, 1968; Ackerman, 1973; Yarger et al., 1978).

Navigational inaccuracies can also be treated by computer analyses or modern high-accuracy navigation equipment may minimize such errors.

A base station monitor will, of necessity, be at a certain distance from the measurement points. It has been found that time variations may strongly depend on location and, for this reason, base station monitors are not recommended for data corrections.

For a salt repository survey, it is recommended that an accurate navigation system be used, such as the "Flying Flagman" system by Del Norte Technology, the Decca "Trisponder", or the Motorola "Mini-Ranger." Navigational accuracy can be further improved by using radar altimeters and doppler radar for speed control. These systems should permit locating flight lines to an accuracy of 3 m or better. In a midlatitude position, a 3-m lateral positioning error is associated with a difference in magnetic intensity of up to 0.04 nT.

With good positioning, a computer processing scheme should eliminate diurnal errors. For very high sensitivity surveys designed to investigate magnetic anomalies orginating in salt and other sedimentary rocks, a vertical gradiometer configuration is recommended. Such a survey could be combined with a detailed radiation survey, using helicopters.

2. Ground Magnetic Surveys - For bedded salt repositories, ground-magnetic surveys would be limited to checking specific locations for fault indications (Aitken, 1961; Breiner, 1973). For this purpose, magnetic readings with a sensitivity of about 1 nT would be taken along lines perpendicular to suspected fault trends. Lines would be located by surveying or map reference, and distances along the lines would be established by tape measure or electronic distance meter.

Ferromagnetic materials on the person of the magnetometer operator or on the ground in the vicinity of the measuring point could influence data results. Diurnal variations would be accounted for by having a second instrument in a fixed base location, or by reoccupying a base station at half-hour intervals.

A.2 GRAVITY MEASUREMENTS

A. Instrumentation

The only type of instruments presently used for terrestrial gravity surveys are gravimeters of the unstable or astatized type, mainly the LaCoste-Romberg or the Worden gravimeters. These instruments contain a weight held in a state of unstable equilibrium by a zero-length spring, that is, a spring which would theoretically return to zero-length if the force acting on it were removed. With this arrangement, the elongation of the spring is proportional to the increment of gravity measured. The range of linearity is relatively small, however, so that these instruments are read by adjusting the weight beam to a null position with a calibrated screw (Dobrin, 1960).

Gravimeters are very sensitive to temperature variations, so that the design of the instruments must incorporate means of temperature compensation. Sensitivity of the LaCoste-Romberg or Worden gravimeters is 0.01 mgal. Gravimeter measurements are not absolute, they show only variations in gravitational acceleration with respect to an arbitrary datum. However, as in magnetic measurements, only the anomalous field related to local geologic conditions is of interest and, in fact, regional variations are normally removed before interpreting the data.

B. Survey Techniques

For a detailed survey of a salt repository site, gravity stations should be located on a square grid with 500-m spacing. For a regional survey covering wider areas of a salt basin, spacings up to 2 km can be used. Spacings can be adjusted according to the variations of the gravity field--i.e., a highly variable field will require closer spacing.

In some locations, one cannot strictly adhere to a square grid pattern. Topography and accessibility may dictate the use of roads and other lines. As described in Chapter 2, a conventional gravity survey requires surveying of station positions to an accuracy of at least 100 m laterally and 30 cm vertically. These are not strict tolerances, but they do require a certain amount of surveying. Microgravity surveys are not required for repository sites because the added accuracy of these surveys is useful only for investigations of near-surface features. A conventional gravity survey is sufficient to define gravity anomalies that may arise from density variations at the depth of a planned repository. Such density variations would have to encompass fairly large volumes of rock in order to be detectable at the surface. This is due to an inherent limitation of gravitational measurements whereby anomalous rock bodies, that are much smaller in size than their depth of burial, are difficult to distinguish from geologic noise caused by shallower gravity variations.

In order to correct for instrument drift and tidal variations, certain base stations will have to be reoccupied every two or three hours. From repeat readings, smooth drift curves can be plotted and subtracted from the instrument readings according to time of measurement.

For terrain and Bouguer corrections to be made in processing the gravity data, it is essential to have a good knowledge of near-surface densities in the area surveyed. These corrections become more significant with increasing irregularity of the terrain. If densities are not sufficiently well known, samples of rocks and soils can be collected and densities determined in the laboratory. A gravity profile across a topographic feature can be used for in-situ determination of density according to Nettleton (1939).

A.3 SEISMIC REFRACTION MEASUREMENTS

A. Instrumentation

Near-surface refraction surveys are usually performed with simple seismographs, called engineering seismographs. Instruments used for the envisioned purpose should have the capability of recording at least 12 channels of seismic data and provide timing for shots and geophone traces with an accuracy of 1 ms. A variety of such instruments is available, some of them having the capacity for summing signals obtained with repeated seismic impulses (signal enhancement seismographs). The seismograph must also include a blasting circuit with zero time mark.

Suitable cables and refraction geophones complete the equipment necessary for refraction surveys. Geophones used for refraction should have a relatively low frequency, usually about 8 Hz.

B. Survey Techniques

Refraction surveys to be conducted at repository sites should define near-surface layering of soils and rocks for engineering purposes and foundation design. Each seismic refraction line consists of placing geophones in a straight line, usually at uniform spacings. The spacing of geophones is chosen according to the depth of layers investigated. Shotpoints are located at both ends of each line, and lines are thereby measured in a forward and reverse direction. This arrangement permits definition of dipping subsurface layers. Sometimes a shotpoint is also placed at the center of the line to fill in gaps in shallow layer information.

Topography is usually not of great concern in engineering refraction surveys. However, if large differences in elevation (over 1 m) exist between geophones, these differences should be measured and corresponding corrections made on the refraction data.

Larger areas are to be investigated by consecutive lines. If great detail is needed, these lines can be overlapped. It is also important to have lines perpendicular to the main alignment used in order to define dips correctly.

A.4 SEISMIC REFLECTION MEASUREMENTS

A. Instrumentation

Modern reflection seismographs use digital tape recording. These instruments can accommodate a large number of input channels (over 100 in many cases) and provide sampling intervals as low as 0.25 ms. They incorporate automatic gain ranging to provide a large dynamic range, and amplitude information is recorded to permit full amplitude recovery. The latter feature is important for modern processing and interpretation procedures which give information on lithology and presence of hydrocarbons.

For bedded salt repository investigations, a reflection seismograph with the following characteristics should be used: digital tape recording with 0.25-ms sampling capability, and gain ranging with full amplitude recovery. These characteristics are especially important for high resolution surveys. The instrument should be complemented by an analog playback system which permits checking of record quality in the field.

Older types of seismographs use analog tape recording or digital recording without amplitude recovery and therefore are not recommended for this study.

For standard reflection surveys, the normal reflection cables and geophones can be used. For high-resolution surveys, it may be advisable to use geophones with a higher frequency of about 25 Hz. Some manufacturers have specialized equipment available for high-resolution surveys, e.g., the "Mini-Sosie" recording system and impact source by Input/Output, Inc.

B. Survey Techniques

1. Standard Reflection Surveys - A line of detectors spaced at equal intervals, usually about 65 m, is used to record reflected wave arrivals. The shot point is located at the center or end of the geophone spread. A horizontal reflecting horizon in the subsurface will produce a hyperbolic curve of arrival times with detectors spaced at increasing distances from the shotpoint. The curvature of the hyperbola can be used to determine subsurface velocities. For shallow horizons, a good hyperbola is obtained with shorter distances, whereas deep horizons require large shot-detector spacing and/or end-on shots--that is, shotpoints at the end of the detector spread.

A variety of seismic sources is available for reflection surveys on land. Dynamite is still the most widely used source, but gas guns, weight droppers, and vibrators are also used. The non-dynamite sources are advantageous in areas where shothole drilling and noise created by shots are undesirable. For such applications, "Vibroseis," a method using truck-mounted vibrators, is probably the most popular.

In most cases, however, dynamite gives superior results. With dynamite it is important to determine the correct shot depth. The shot should be located in competent beds below the low-velocity surface weathered layer. Certain types of rock or soil are better than others for producing higher quality seismograms. For instance, in a sand-clay sequence, it is better to locate the shot in clay. Size of shot and velocity of the explosive have to be tailored for the results desired, and some experimentation is required at the start of a survey.

The first problem in reflection surveys is interference caused by slow surface waves, called ground roll. In order to attenuate such waves, geophones are arranged in groups at discrete intervals along the geophone cable. The number of geophones to be used per group and their spacing require a certain amount of experimentation in order to determine the best attenuation characteristics for a given location.

A second problem is caused by multiple reflections--that is, by waves that are reflected downward from the earth's surface, which has a high reflection coefficient. After being reflected by a subsurface horizon a second time, such waves arrive at the surface with an increased travel time that suggests a nonexisting deeper horizon. Although multiple reflections originating from the surface are the most common, other multiple reflections occur between subsurface horizons.

Two means are available for eliminating or attenuating such undesirable events. One is a field procedure called common depth point (CDP) stacking (Mayne, 1962; Marr and Zagst, 1967); the other is a mathematical procedure called deconvolution (Peacock and Treitel, 1969), which is used during processing of the data. In common depth point stacking, seismic lines are overlapped so that consecutive lines cover the same subsurface points a number of times. With appropriate length of the detector spread, the hyperbolas for a given travel time caused by actual reflections will have less curvature than hyperbolas caused by multiple reflections. By summing several reflections from the same subsurface point and with different shot-detector lengths, as is the case with overlapping lines, the actual reflections can be amplified and multiple reflections attenuated. A common amount of overlap used is six-fold subsurface coverage (600 percent stack).

The deconvolution procedure used in decoding extracts from the data an estimate of the seismic input wavelet based on the assumption that reflection coefficients in the subsurface approximate a series of random numbers. The seismogram recorded is then convolved with an inverse wavelet which attenuates multiple reflections.

A third paramater requiring close attention is the variability of thickness and velocity in surface layers, collectively referred to as the weathered layer. Because of their low seismic velocity, these surface layers can introduce considerable time delays into the data which make proper correlation of traces difficult. Travel times measured from the shotpoint at depth to a geophone near the shothole at the surface (uphole time) are an important factor in correcting for surface variations and are one reason for the good results usually obtained with dynamite. Other information on velocity and depth of the weathered layer is obtained from refraction calculations, either from the reflection recordings or from separate weathering shots.

Because of these weathering corrections, elevations of shots and detectors must be known to an accuracy of about 30 cm. In rough terrain this requires surveying. Data corrections related to elevation and weathered layer are called static corrections. After known factors have been entered into these corrections, modern processing methods permit fine tuning of the data via automatic static corrections. These automatic corrections are especially important for high-resolution surveys.

2. High-Resolution Reflection Surveys - The aim of high resolution surveys is to provide greater detail and higher accuracy for certain subsurface strata. Geophone group spacings are therefore reduced to about 15-20 m.

In addition to tighter spacings, high-resolution surveys employ higher frequencies for sharper definition of layers and for detecting thinner beds. According to Farr (1979), the presence or absence of a bed in the subsurface can generally be detected if the bed is as thick as one-eighth of a seismic wavelength. The best resolution to be expected is about one twelfth of a wavelength, whereas, in the worst case, a bed with a thickness of one-quarter of a wavelength should be detectable. Widess (1973) stipulates that the minimum thickness of a bed for which both upper and lower boundaries can be defined is one-quarter of a wavelength.

Employing higher frequencies in a high-resolution survey involves several steps. First, the seismic source has to produce predominantly high frequencies which, in the case of a dynamite source, means using smaller charges, since there is an inverse relationship between charge size and frequency content of the seismic wavelet. Frequencies generated range up to a maximum of 1000 Hz.

If the smaller charge does not produce a strong enough signal, then a summing procedure is employed whereby several shots in the same location are recorded and the resulting records summed in order to amplify reflections and attenuate random noise. This type of procedure is used particularly with low-energy sources such as gas guns or surface weight impacts. For instance, the "Mini-Sosie" method of high-resolution seismic reflection (Wiles 1979) relies on a great number of repeated impacts produced by an earth tamper.

High-frequency response also requires high-frequency geophones and high-frequency recording system response, which depends principally on the sampling rate used. Smaller geophone group spacings result in smaller shot-detector spacings which again favor high-frequency response. Other measures employed to emphasize high frequencies are the use of near traces only (which further decrease shot-detector distances), and reduced stacking (stacking acts as a low-pass filter).

High-resolution surveys result not only in better definition of beds at depth, they can also reduce the minimum depth at which a consistent reflection horizon can be found. Experience shows that the shallowest level that gives valid reflections is on the order of 100 to 150 m. Above this level, reflections are obliterated by surface waves and refracted waves. Further improvement in resolution of shallow horizons could be achieved by using near traces only. Because of the reflection method's depth limitation, refraction surveys are generally used for shallow horizons.

A.5 ELECTRICAL AND ELECTROMAGNETIC MEASUREMENTS

A. Instrumentation

Equipment from several manufacturers is available for measuring currents and potentials to desired accuracy, and for switching currents. For deep penetration it is essential to have a large generator with a capacity of up to 50 kW. A summing device is recommended which permits addition of successive signals and thereby reduces the required power capacity.

B. Survey Techniques

A number of different surface configurations are used for the current and potential electrodes. Both sets of electrodes are laid out along a line for all configurations with the current electrodes usually placed on the outside of the potential electrodes. Electrode spacing may be either fixed or variable. In the first case the array is moved with constant separation from one place to another and apparent resistivities are plotted at the mid-point. In the second case, the center of the electrode spread remains fixed and the separation of electrodes is progressively increased until the maximum desired depth of penetration is reached. With these increasing spacings, a profile of apparent resistivities versus spacing can be plotted which gives information on the variation of subsurface resistivity with depth.

A.6 MICROSEISMIC MEASUREMENTS

A. Instrumentation

Microseismic instruments are self-contained units (Westphal and Lange, 1966, 1967; Prothero and Brune, 1971; Oliver et al., 1966; Lehner and Press, 1966) which can be left in the field for a period of time to record seismic movements. Analog chart recorders and digital tape recorders are available; the instruments can be set up to record a vertical geophone component or three components. The advantage in digital recording is high dynamic range and low system noise. Time marks are provided (usually at 10-s intervals) on paper charts, and recording speeds of at least 1 mm/s are available. Instruments for either rock noise or microearthquakes are available from a variety of manufacturers. Some universities, however, prefer to make their own specialized seismographs.

Many of the modern microseismographs operate as event recorders rather than as continuously recording instruments. Microseismic event recorders, like strong motion seismographs, record only events whose amplitude exceeds a preset threshold level. Usually, a continuously recording and recycling tape is included which permits recording of low-level events immediately preceding the event that triggers a recording. Since microseismic events are, by definition, low-level events, design of the trigger system is critical. The trigger must be sensitive enough to record all significant events with few or no false alarms.

Geophones used for microseismic measurements should have a low frequency (approximately 1 Hz) and high sensitivity. Several designs are available for use on the surface or in boreholes.

B. Survey Techniques

1. Rock noise measurements - This type of measurement is recommended for monitoring bedded salt repositories during and after construction. Geophones that pick up sound emanations should be located at strategic locations throughout the repository and in access shafts. A second set of geophones may be placed in shallow boreholes at the surface. Groups of geophones can be connected to central recording stations.

Ground noise recordings may identify zones of weakness and incipient fractures. Increasing activity in a given area may precede structural failure. During the emplacement and decommissioning phases of the repository, thermal conditions may induce stresses in the repository that could lead to failure. Rock noise monitoring, therefore, is particularly important during these phases for monitoring the condition of the repository.

2. Microearthquake measurements - During the repository siting stage, at least three microseismographs should be located in the area of interest. Microearthquake activity is then monitored for a period of time from a few days to several months. If a given location shows no activity, the instruments can be moved to a different location.

In areas where access is difficult, it is advantageous for the instruments to be self-contained and able to record for a considerable length of time. Alternatively, microseismographs can be connected via telemetry links to a central recording station.

With three instruments, a preliminary determination of earthquake foci can be made. However, if sufficient activity is recorded to necessitate further investigation, then additional microseismographs should be placed in the same area. With the additional instruments, earthquake foci can be pinpointed much more accurately. The redundant data provided by additional seismographs also make it possible to estimate the precision with which the foci are determined.

Microearthquake measurements permit determination of epicenter locations and depths and of focal mechanisms of small earthquakes. In addition, studies of foreshock and aftershock patterns and of earthquake frequency provide insight into the mechanical structure of and the nature of stresses in the repository medium.

Newer signal processing and correlation techniques (Katz, 1976) have made it possible to relate details of microseismic recordings to local geologic structure. By emphasizing vertically traveling microtremors, it has also been possible to construct seismic time sections similar to those obtained from seismic reflection surveys (Weller, 1974).

A.7 ELECTRICAL RESISTIVITY LOGGING

A. Single-Electrode Method

In this method, the resistivity curve is obtained by recording the resistance changes of a single electrode placed in the hole. As the logging electrode moves in the hole, changes in the resistivity of the surrounding material cause changes in the electrode resistance, accordingly changing the voltage in the logging circuit. The lateral penetration, which is approximately ten times the electrode diameter, is not as extensive as in multiple-electrode measurements (Roy and Dhar, 1971).

The single-electrode method is not recommended since it measures only apparent resistivities; these may be considerably different from actual values as determined by the multiple-electrode technique (mentioned below). Further, the single-electrode resistivity curve loses some detail if the drilling mud is salty, as would probably be the case near the salt repository.

B. Normal Arrangement

The normal arrangement is a multiple-electrode technique with one current and one potential electrode located downhole on the logging sonde and a potential and current electrode at the surface. The current and potential electrodes are 16 inches apart on the downhole sonde in the short-normal arrangement, and 64 inches apart in the long-normal arrangement. The effective penetration into the surrounding material is about twice the electrode spacing. The accuracy of normal logs decreases with an increase in the hole diameter and with a decrease in drilling mud resistivity. Effects of adjacent beds and porous zones of drilling mud can be reduced by the use of published correction charts.

The short-normal spread can be used to measure porosity, since it gives the resistivity of the porous zone that is invaded by drilling mud surrounding the borehole.

The long-normal spread measures a resistivity that is intermediate to the actual formation resistivity and the resistivity of the zone affected by drilling fluid.

C. Lateral Arrangement

The lateral arrangement consists of two downhole potential electrodes 32 inches apart. The nearer downhole current electrode is normally 18 feet 8 inches from the center of the potential electrode arrangement. The depth of penetration is approximately equal to the spacing between the near current electrode and the center of the potential arrangement.

For relatively thick homogeneous beds, the method yields the true formation resistivity. A combination of normal and lateral electrode arrangements allows determination of the actual formation resistivity as well as the extent and resistivity of the zone invaded by the drilling fluid (Telford et al., 1976).

D. Microlog

The microlog arrangement consists of two downhole potential electrodes and one downhole current electrode embedded in an insulating pad that can be expanded to press against the side of the borehole. Separation of the electrodes is approximately one to two inches, and depth of penetration is a few inches at most.

The microlog is useful in obtaining qualitative information on both porosity and lithology. It can also be used as a caliper to determine borehole diameter.

E. Focused Current Logs

The focused current method consists of focusing the current into a thin disk which penetrates laterally into the surrounding rock rather than flowing up the walls of the hole as in the methods mentioned above. This method allows determining true formation resistivity in very thin beds without being affected by conductive drilling fluid as is the case with the methods mentioned above.

A number of different electrode arrangements have been devised using focused currents, including the guard log or laterolog (Doll, 1951), and the microlaterolog or trumpet log (Doll, 1953).

Depth of investigation varies from a few inches to several feet, depending on the type of method used. Depth of penetration using the guard log is approximately three times the length of the guard electrode.

F. Induction Log

Induction logging uses the same technique as surface electromagnetic testing. The induction log measurement is proportional to the electrical conductivity of the formation.

Depth of penetration is approximately three-fourths of the spacing between the transmitter and receiver for unfocused systems and twice the spacing for focused systems. Focused systems minimize the effects of mud resistivity, hole diameter, and the zone of drilling fluid invasion. By adjusting the response to peak at discrete distances from the borehole, resistivity can be measured for different depths of penetration.

Although resolution is poor if highly conductive muds are used, the induction log may be used in dry holes where other resistivity methods may not prove effective. The induction log is also more useful in determining geologic structure and formation dips than the other methods mentioned above.

G. Dipmeter and Fracture Identification Logs

The dipmeter is used to determine formation dip (De Chambrier, 1953). Although instruments in the past measured EM-response or self potential, current instruments employ microresistivity measurements.

The instrument consists of either three pads pressed against the borehole wall at 120-degree intervals or four pads at 90-degrees. The instrument contains an inclinometer to measure the borehole angle and bearing, and a magnetometer to determine the azimuth. A caliper log is also included.

A dipmeter log consists of the relative bearing of the hole drift and the azimuth with respect to the Number 1 electrode, the hole deviation, the caliper log, and the resistivity log of the pads.

From differences in the depth of lithological boundaries around the borehole and the orientation data, strike and dip of the surrounding formations can be obtained. Dipmeter measurements can also be used to locate vertical fractures (Brown, 1979). The focused measurements made with the dipmeter are extremely sensitive to changes in resistivity. When one of the pads crosses a fracture filled with mud, it records a relatively lower resistivity than the pads facing an unfractured section of borehole. Computational analysis and correlation of many close spaced data points are generally required for quantitative interpretation of the data.

An advancement in the dipmeter log to obtain more reliable location and orientation of vertical fractures is the Fracture Identification Log (Brown, 1979). The instrument consists of four dipmeter microresistivity pads oriented at 90-degrees.

Data presentation consists of two parts, the first shows the four dipmeter correlation curves independently and the second shows the four curves in a dual two-curve overlay.

Permeable beds can be distinguished from vertical fractures with the four-curve presentation, since permeable beds will show sharp excursions on all curves, while vertical fractures will generally show excursions on only one or two curves. The two pads in an overlay pair are 90-degrees apart. When a vertical fracture is crossed, it will usually be observed as an anomaly on only one pad of a pair. The anomaly will result in a separation between the curves and indicates the possible presence of a vertical fracture.

A.8 ACOUSTIC LOGGING TECHNIQUES

A. Sonic Velocity Log

The sonic velocity log is used to determine sonic wave velocity. In order to eliminate errors in arrival times, the difference of arrival times at two receivers at different distances is measured. This procedure eliminates effects opposite the transmitters. Two transmitters are used to eliminate effects opposite the receivers, one located above the receivers and the other below them.

The principal application of sonic velocity logs is in porosity investigations.

B. Sonic-Amplitude Log

Although the sonic log measures only the arrival time of the first wave, the wave amplitude is also an important parameter. Fractures cause the acoustic amplitude to decrease markedly. Generally, the compressional wave is more attenuated by high-angle and vertical fractures, and the shear wave is attenuated by low-angle and horizontal fractures.

Care must be taken, however, when using the amplitude change without other corroborative evidence as an indication of fracturing. Changes in wave amplitude may be caused by other factors, including variations in lithology, porosity, and borehole size. Furthermore, healed fractures may give the same response as the surrounding rock.

Cycle skipping is the result of reduced amplitude of the acoustic signal. The reduction in signal amplitude is caused by high reflection of energy and low transmission of energy at the fracture interface. Consequently, the first arrival of the compressional wave is not detected and travel times are longer than those generally recorded. If travel times are longer than the times generally recorded, cycle skipping has occurred. This phenomenon allows the detection of fractures.

C. Variable Intensity Log

The entire wave train arrival is recorded on the variable intensity log. Amplitude changes are indicated by variations in shading across the film track. The darkest shades correspond to the greatest positive amplitude and lightest shades to the greatest negative amplitudes.

The log appears systematically banded if the section is unfractured and the lithology and porosity relatively constant. Banding is highly discontinuous if the log is run through a fractured section.

Care must be taken when interpreting these logs, however, since breaks in the banding can also be caused by changes in lithology or porosity.

A.9 NUCLEAR LOGGING TECHNIQUES

A. Natura' Gamma Radiation Logs

The sonde used for gamma-ray logging consists of a dectector and an amplifier (Kokesh, 1951). A scintillation counter is the best tool for measuring the weak gamma-ray intensity in a well at the speed necessary to obtain a log in a reasonable time. Earlier models used less efficient Geiger counters or ionization chambers. Below 5000 feet, the scintillation counter may have to be replaced by other types of detectors because of problems, resulting from high temperatures.

Gamma-ray logs can be used in cased holes, although the curve amplitude is somewhat reduced. They can also be run in dry holes or holes containing salt water or salty mud, where electric logs are generally poor. Mud has two effects on the gamma-ray curve. It reduces the log amplitude by absorbing a small percent of the radiation. This effect can be ignored unless the hole has a very large diameter (more than 2 feet). Also, the shale or clay contained in the mud somewhat increase the background radiation.

Since radioactive elements concentrate in clays and shales, the gamma-ray log reflects mainly the shale content in sediments and can generally be correlated with the self-potential log. It is more effective than the self-potential log in highly resistive formations or where there is little difference between the salinity of the drilling mud and the formation water.

If beds are thin or if the logging speed is too great, the probe leaves the bed before it can measure the full change in radioactivity because of the delaying action of the instrument time constant. The logging speed must be adjusted in relation to the instrument time constant to avoid loss of sensitivity. The amplitude of the gamma-ray curve is therefore smaller in thin beds than in thick beds, all other factors remaining constant. Initial borehole gamma-ray readings can be used to establish a baseline for the normal background radiation with which future measurements can be compared and anomalous areas of radiation increase identified.

B. Density Logging (Artificial Gamma Radiation Logging)

The primary application of density logging has been the determination of formation porosity, since density is related to porosity (Pickell and Heacock, 1960).

Instrumentation for density logging includes a sonde with a monoenergetic gamma ray source at the base and a detector such as a scintillation counter about 18 inches above the source. The sonde is forced against the borehole wall by a spring. The radiation path is through the adjacent rock, since the sonde is surrounded by lead shielding except for a window that faces the hole wall.

The gamma rays from the source interact with the surrounding rock and the detected gamma ray intensity is a function of the rock density. The maximum depth of penetration is approximately 6 inches and most of the detected signal returns from within 3 inches of the hole wall.

Density logging may be used in either dry or fluid filled holes. The logging speed must be adjusted to the instrument time constant to avoid loss of sensitivity.

Porosity can be determined from a standard formula using the bulk density, the density of the fluid, and the density of the matrix. Methods have been devised to cancel background radiation and measure the net bulk density. One method requires the making of two logs with differences in source-to-detector spacings of about 4 inches. The source spacing can be varied in the hole to complete both logging runs on one trip. The difference method is used to calculate bulk density and porosity. It essentially eliminates the effects of natural gamma radiation.

C. Neutron Logging

Neutron logs are also used to determine formation porosity. Neutrons are emitted from a source in the logging tool, and bombard the walls of the hole (Pontecorvo, 1941). Slowing and capture of the neutrons is proportional to the abundance of hydrogen near the source. Therefore, the activity measured by the log will be inversely proportional to the water content of the surrounding medium. If the formation is saturated, the activity will also be inversely proportional to the porosity.

A number of neutron sources have been used with varying half-lives and neutron yields. The sources include beryllium in combination with an alpha source such as plutonium, radium, or polonium. Charged particle accelerators are also used to produce neutrons.

Several types of detectors have been used. Some are sensitive to thermal neutrons as well as to gamma-rays resulting from neutron capture. Other sources detect neutrons with energies above a certain threshold level.

In saturated, porous material the neutrons lose energy rapidly; hence, penetration distance is short--i.e., only a few inches from the borehole. In low-porosity material, a penetration of approximately two feet can be achieved. Highest resolution is obtained in small-diameter boreholes so that little energy is lost to the mud column.

The sidewall neutron log measures epithermal neutrons. These are high-energy neutrons that are not affected by neutron absorbers such as boron and chlorine. The sidewall neutron log is least affected by the chemical composition of the rocks and fluid and, accordingly, should provide a more accurate measurement of total porosity in saturated rock. If a compensated log is used with two detectors spaced at different distances from the source, it is possible to correct for mud effects and hole roughness.

A.10 INSTRUMENTATION AND FIELD TECHNIQUES FOR CROSSHOLE SHEAR-WAVE MEASUREMENTS

In crosshole shear-wave measurements, an impulse source is placed in one borehole, and geophones are placed at the same elevation in one or more adjacent boreholes. For measurements at repository sites, a mechanical impulse source, called a shear-wave hammer, is to be used. This source represents the state-of-the-art in shear-wave measurements and yields excellent results. Older techniques, such as the use of explosives, are difficult to interpret and may give erroneous results.

The shear-wave hammer consists of a stationary part with hydraulic system and pressure plates, and a moving weight attached to a tension cable. By applying hydraulic pressure, the plates can be expanded and the shear-wave hammer clamped to the borehole wall. The hydraulic pistons that press the plates against the borehole wall are also used to retract the system by reversing hydraulic pressure. After retracting the plates, the hammer can be raised or lowered to the next measurement level.

The moving weight assembly consists of two steel weights connected by vertical rods which slide in bearings in the stationary part. The weight assembly can be raised or lowered with the tension cable to strike the stationary part, thus creating shear waves at the contact between plates and borehole wall. Upward and downward impacts of the weight create vertically polarized shear waves with opposite phase. This phase reversal with opposite impacts permits positive identification of shear-wave arrivals because compressional wave polarity remains constant.

A geophone in an adjacent borehole is used to detect arrival of shear waves generated by the hammer. Since shear waves propagate only in a solid medium, it is essential that the geophone is placed firmly against the rock or soil. This contact is accomplished by clamping the geophone to the borehole wall with a pneumatic diaphragm.

A detector in the shear-wave hammer generates an electrical signal at the time of weight impact. Travel time of shear waves is measured from this moment to the arrival of the wave at the geophone.

In order to calculate shear-wave velocities from arrival times, the exact distance between shear-wave hammer and geophone must be known. The distance is determined by surveying borehole locations at the surface and by performing a deviation survey for each borehole used in shear-wave measurements. From these data, the accurate distance between boreholes at each depth level can be computed.

It is well known that shear waves propagate with a lower velocity than compressional waves in a given medium. Because of this fact, shear waves were difficult to identify on records obtained with earlier shear-wave methods, such as measurements using explosive sources. The shear-wave hammer system has two built-in advantages that permit positive identification of shear-wave arrivals. First, the hammer generates vertically polarized shear waves which are detected by a vertically recording geophone. Compressional waves generated by the hammer impact and traveling to the geophone are horizontally polarized. Therefore, shear waves recorded by the system have much greater amplitudes than the compressional waves. Second, the geometry of the shear-wave hammer is such that reversal of impacts produces shear waves of opposite polarity. Compressional wave polarity remains the same regardless of the direction of impact. This second feature permits shear-wave identification even under noisy field conditions.

The shear-wave hammer requires a borehole of at least 4 inches in diameter, whereas the geophones can be used in boreholes down to NX-size. The distance between hammer and geophone is generally kept in the range from 10 to 40 feet. In soft soils, boreholes can be cased without affecting the shear-wave measurements, as long as the casings are in good contact with the surrounding soil. This may be accomplished by proper grouting methods.

Cross shear-wave measurements are a technique used for accurately determining rock mechanical parameters of a limited volume of rock or soil. The parameters measured are used in engineering design. If shear-wave data of a regional nature are desired, shear-wave refraction and reflection data should be used in conjunction with microseismic and other seismological data. Renewed interest in various modes of shear-wave reflection arrivals is being shown by the oil industry for lithologic studies. Further research in this direction is required.

Equipment presently used in crosshole shear-wave studies is limited to depths of about 500 feet. A self-contained system without this depth limitation should be developed for deep repository studies.

APPENDIX B
ROCK MECHANICS: STRESSES,
DEFORMATION, AND THE
CREEP PHENOMENON

B.1 IN-SITU ROCK STRESS

Every element of rock in the earth is subjected to a number of different classifications of stress. These include (Bielenstein and Barron, 1971):

- Natural overburden stresses
- Tectonic stresses caused by geologic forces outside of the immediate area
- Induced stresses arising from stress concentrations around openings
- Induced thermal stresses
- Residual stresses resulting from changes in stress history.

If an opening is created for a repository in a salt bed, stress concentrations will be induced in the rock around the perimeter of the opening.

The magnitude of these induced concentrations will .end upon the weight of the overburden rock, acting vertically, together with a horizontal stress caused by vertical compression without lateral expansion, plus tectonic stresses if they are present, plus any active residual stresses. In addition, if the rock stratum is locally heated or cooled above or below ambient temperatures, thermally induced stress changes will arise in the rocks. If the stress state is determined at any point in a rock mass, the stress measured will include all of the above stresses. These values, as determined by overcoring, can be used for design because they represent the actual stresses in the rock. The main objective of in-situ stress determinations is to measure these stresses.

- Natural overburden stresses are caused by the weight of the overburden. They consist of a vertical component due to overburden rock weight, a horizontal component due to the elastic confinement of the rock element, and shear components due to differences in rock properties of the overlying strata.

- Tectonic stresses are caused by geologic processes such as volcanic activity, global plate movements and other deep-seated activities.

- Induced stresses are caused by excavation. If an opening is cut into a stressed rock, the stresses in the rock around that tunnel adjust to the removal of support and confinement. The result is a pattern of increased stress around the perimeter. The exact pattern depends on the depth of the opening, the properties of the rock, and the original stress distribution.

- Induced thermal stresses are caused by the heating or cooling of localized masses of rock above or below ambient temperatures as determined by the regional geothermal heat flow. Heating causes the rock to expand and thus press outward against the unheated rock. Cooling causes the rock to contract and thus reduces the outward stress against the surrounding uncooled rock. In both cases, the stress patterns around the regions of temperature changed are altered.

- Residual stresses are of two types:
  - Fabric residual stresses
  - Structural residual stresses.

Fabric residual stresses have been observed in many types of rock. They are characterized by time-dependent strain recovery of unloaded freshly cut rock samples. This recovery can be explained as follows:

- The deep burial of a rock element causes rearrangements in component mineral crystal lattices to reduce internal stress concentrations caused by differing amounts of strain in each crystal. When the burial pressure is reduced, the compressed crystals expand, again by different amounts, resulting in the development of intergranular stress concentrations. With time, microfracturing or plastic flow on the microscopic scale results in strain relaxation, and the stress concentrations dissipate.

Structural residual stresses also arise out of differences in rock properties; however, the restraints upon strain are due to geologic structure and not rock fabric configurations. An example can explain the process:

- Assume that a series of salt beds is buried at depth and that the horizontal and vertical stresses are equal. Without differential stress, the beds can remain in equilibrium without creep indefinitely. If overburden is rapidly removed, the vertical stresses will relax; the horizontal stresses will also tend to relax, but by a lesser amount due to the elastic properties of the salt. The total vertical stress can be removed, but the total horizontal stress cannot because the reductions in stress can never total the original horizontal stress. The result is the creation of high horizontal stresses near the surface. High horizontal stresses have been recorded by many investigators for numerous mines and caverns in hard rocks (Herget, 1973).

It is expected that the cumulative effect of all the above sources of in-situ stress will lead to a stress distribution underground that will vary both locally and regionally. A reasonable number of stress determinations will lead to an understanding of the rock stress pattern in a repository in bedded salt.

B.2 STRESS DEFORMATION BEHAVIOR PARAMETERS

Stress-deformation phenomena are classified int four basic idealized mechanical states:

- Elastic Behavior
- Plastic Behavior
- Creep Behavior
- Post-Failure Behavior.

For each state, the deformation that results from the application of stress is determined by a different set of rules. The parameters that represent those rules (physical properties) vary not only by rock type, environment, and fracture history, but also by mechanical state.

Parameters that are not dependent upon the mechanical properties or the mechanical state as defined above are

σ	Stress (psi)
δ	Deformation (inches) (or strain ε, dimensionless)
T	Temperature (^{o}F).

Elastic behavior is characterized by a linear relationship between stress and strain. Strains are small and no internal changes in rock fabric occur. Parameters to measure are

E	Young's Modulus (psi)
G	Shear Modulus (psi)
ν	Poisson's Ratio (dimensionless).

Plastic behavior is characterized by a change of state in the matrix of the rock in which permanent deformations occur. Upon the release of stress not all of the strain is recoverable; the recovered portion is the elastic strain and the nonrecovered portion the plastic strain. Ideally, plastic strain does not begin until a minimum stress, the yield stress, has been reached. Parameters to measure are

σ_Y	Yield Stress (psi)
σ-ϵ Curve	Stress-strain curve for various stress conditions.

Creep behavior is characterized by time-dependent strain under a constant stress state. It can occur in non-yielding rocks as well as in rocks that have been raised above their yield point. It can also occur in failed rocks. A full discussion of creep is given in Sections B.3 and B.4 of this Appendix; measurement techniques are described in Section B-5 (laboratory) and Section 3.5F (in-situ).

Post-failure behavior is characterized by a negative stress-strain relation. Most rocks, under normal stress conditions found underground, are brittle and not [illegible]tic. They fail by progressive fracturing under a relaxing applied stress. In the failed state any increase in stress leads to an immediate total failure of the rock. However, a decrease in stress is accompanied by an increase in strain, and thus equilibrium is maintained without a total collapse of the fabric. In many mines and underground civil structures, failing but stable rock masses exist in pillars, walls, roofs, and floors. Parameters that can be measured are

σ_{f_u}	Unconfined failure strength (psi)
σ_f - ϵ_f Curve	Stress-strain envelope for triaxial tests under varying confining stress
F	Failure modulus--slope of stress-strain curve for failure (negative slope) (psi)
E_f	Elastic modulus of failed rock (psi)
G_f	Shear modulus of failed rock (psi)
ν_f	Poisson's ratio of failed rock (dimensionless).

B.3 CREEP LAWS AND PARAMETERS

The creep strain within a rock is a function of time, the state of applied stress, the pore-water pressure, temperature and the internal state of the rock fabric. Normally, the following functional relationship is assumed:

$$\varepsilon = f_1(t)\, f_2(\sigma)\, f_3(T)$$

Where ε is total strain, t is time, σ is stress, and T is absolute temperature. Pore pressure effects are assumed to enter into the relationship by means of the effective-stress principle in which the principal stresses (σ) are replaced by the effective stresses (σ'), where

$$\sigma' = \sigma - p$$

and p is the pore pressure.

The internal state of the fabric must enter into the relationship through the functions f_1, f_2, and f_3. A change in these functions indicates a change in creep mechanism within the rock fabric.

The state of stress acting upon rock elements within the earth is always triaxial. But our understanding of the creep phenomenon in rocks comes from laboratory tests--either uniaxial tests or triaxial tests--in which the intermediate and minor principal stresses equal the confining pressure. The driving force for creep is differential stress, or a higher principal stress minus a lower principal stress. For most applications, it is the maximum principal stress less the minor principal stress. For laboratory uniaxial creep tests, the differential stress is the axial stress, while for triaxial tests, it is the axial stress less the confining pressure.

In laboratory creep tests, the common testing technique is suddenly to apply a constant differential stress to a core sample in a testing machine and then to monitor axial deformations over time. Three basic stages of creep are always recognizable:

- Primary creep--a higher initial creep rate decreases steadily with time toward a constant value

- Secondary creep--the creep rate remains essentially constant up to a period in time where it then begins to increase

- Tertiary creep--the creep rate, upon increasing, continues to increase until failure occurs.

The duration of each stage depends upon the axial load and the rock being tested. For most rocks, when differential stresses are above three-quarters of the specimen strength at a given confining pressure, secondary creep does not develop. Also, when differential stresses are below one-quarter of the strength, long periods of time are normally required before tertiary creep can develop.

Time Laws

In analyzing creep behavior, the following equation can be used. For a sample loaded under stress σ and at temperature T, strains are

$$f_1(t) = \varepsilon_i + \varepsilon_p(t) + \dot{\varepsilon}_s t \qquad \text{(Lama and Vutukuri, 1978)}$$

where f_1 (t) is total creep strain, ε_i is the initial elastic strain, $\varepsilon_p(t)$ is the primary creep time law, and $\dot{\varepsilon}_s$ is the secondary creep rate.

Table B-1 shows the most commonly used primary creep time laws and to what rocks these laws are applicable. Also listed are the parameters that are applicable to each law. These parameters are the ones that must be used when employing mathematical models for analyzing in-situ creep behavior of a rock.

TABLE B-1

TIME LAWS FOR ROCK CREEP

LAW	DESCRIPTION	CREEP PARAMETERS	ROCK	REFERENCES
Primary Creep				
$\epsilon_p(t) = At^m$	Parabolic Law	m ($0 \leq m \leq 1$)	Salt Limestone Marble Gabbro Granodiorite	Misra and Murrell, 1965; LeComte, 1965; Lomenick and Bradshaw, 1969; King, 1972; Starfield and McClain, 1973; Wawersik, 1974
$\epsilon_p(t) = At^m + Bt^n$	Polynomial Law	m,n	Numerous rocks at high temp.	Misra and Murrell, 1965
$\epsilon_p(t) = A \ln t$ $\epsilon_p(t) = A \ln (1 + \alpha t)$	Logarithmic Laws		Gabbro Granodiorite Granite Shale Mudstone Limestone Sandstone	Griggs, 1936; Lomnitz, 1956; Price, 1964; Misra and Murrell, 1965; Hobbs, 1970
$\epsilon_p(t) = A\,(1 - e^{-t/n})$	Viscoelastic Law	n	Limestone Sandstone	Hardy, 1967
Secondary Creep				
$\epsilon_s(t) = (A/n)\,t$	Maxwell Viscoelastic Law	n	Limestone Talc others	Griggs, 1936
Tertiary Creep				
$\epsilon_t(t) = At^p$	Parabolic Law	p ($p \geq 1$)		

For secondary creep, the strain rate is constant and not a function of time:

$$\dot{\epsilon}_s = \eta$$

The parameter η is a function only of stress level, temperature, and the internal state of the rock fabric.

For tertiary creep, no specific time laws have been proposed, since few creep experiments have been designed specifically to investigate it. When tertiary creep begins, it denotes impending failure, so that in most cases the main interest of analysis is to recognize when secondary creep ends and tertiary creep begins. A parabolic law with an exponential term larger than unity is applicable.

Stress Laws

The stress dependence of creep has two facets: a differential stress dependence and a confining stress dependence (Cogan, 1976). In a uniaxial test, the axial stress dependence dominates. An increase in axial load results in an increase in axial creep rate. In a triaxial test, the differential stress dependence is modified by confining pressure because, at very high confining pressures, changes in the creep mechanism occur. Table B-2 presents stress-dependent laws and their associated rocks. These laws are assumed to be applicable to both primary and tertiary creep.

A detailed knowledge of how confining pressure affects creep in many rock types is still lacking. For salt it appears that creep is driven by differential stress only (LeComte, 1965; Carter and Heard, 1970)--i.e., equal amounts of axial creep can occur in a sample at different confining pressures because only axial stress less confining stress controls creep rates. This condition is probably true for many rocks

TABLE B-2

COMMON STRESS-DEPENDENT RELATIONS
FOR ROCK CREEP

LAW[1/]	DESCRIPTION	CREEP PARAMETERS	ROCK	REFERENCES
$\dot{\varepsilon} = A\sigma^n$	Parabolic Law	n [2/] $(1 \leq n \leq 8)$	Salt Sandstone Siltstone Shale Limestone	Robertson, 1963; Obert, 1965; Hobbs, 1970; Cruden, 1971 a, b
$\dot{\varepsilon} = Ae^{B\sigma}$	Exponential Law	B	Marble	Heard, 1963; Donath and Fruth, 1971
$\dot{\varepsilon} = \sinh N\sigma$	Hyberbolic Law	N	Marble Sandstone Limestone	Griggs, 1940; Heard, 1963

1/ $\dot{\varepsilon}$ = strain rate $\frac{d\varepsilon}{dt}$

2/ If n = 1, the law is one of viscoelasticity (Maxwell body).

until confining pressure values become so large that internal creep mechanisms change.

Confining pressure strongly affects creep in weak and fractured rock and in post-failed rocks because confining pressure tends to close cracks. In fact, Cogan (1976) found that large confining pressures applied to shales introduced a consolidation effect which strongly retarded creep rates.

Temperature Laws

An increase in temperature always causes an increase in creep rate. The total creep strain is the sum of a number of microscopic creep strains distributed throughout the rock fabric. Past investigations have assumed that these microscopic creep events are thermally activated, so that an increase in temperature increases the rate of activation and thus the strain rate (Heard, 1963; LeComte, 1965; Misra and Murrell, 1965).

A list of temperature laws is shown in Table B-3. The exponential law is the typical rate-process temperature term used in chemistry and physics. The linear law is taken from Misra and Murrell (1965) and was derived from Mott's theory of creep (Mott, 1952). The parabolic law is a purely empirical relationship taken from laboratory experiments.

TABLE B-3

TEMPERATURE DEPENDENCE LAWS
FOR ROCK CREEP

LAW[1]	DESCRIPTION	CREEP PARAMETERS	ROCK	REFERENCES
$\dot{\varepsilon} = \exp[-\Delta H/kT]$	Activation Law	ΔH = Activation Energy Constant	Anhydrite Dolomite Sandstone Marble Salt	Misra and Murrell, 1965; Carter and Heard, 1970
$\dot{\varepsilon} = AT$	Linear Law	None	Dolomite Sandstone Granodiorite	Misra and Murrell, 1965
$\dot{\varepsilon} = AT^n$	Parabolic Law	n	Salt	Lomenick and Bradshaw, 1965 and 1969; Starfield and McClain, 1973

[1] strain rate: $\dot{\varepsilon} = \frac{d\varepsilon}{dt}$

Pore-Water Effects

The effects of pore water upon rock creep have been minimally investigated and therefore are not well understood. The effective-stress principle probably applies, but proof of this is lacking. For dry rocks humidity has an effect upon creep; the drier the rock, the lower the creep rates (Wiid, 1970). Thus, the drying out of a rock due to high temperature may lead to a decrease in creep rate which may offset the increase due to a temperature rise. This case has been observed in concrete (Neville, 1970). No research has been reported in these areas for bedded salt.

Internal Fabric Effects

The state of the internal fabric of a rock strongly affects creep also. The two major divisions to consider are

- Prefailed State
- Failed State.

In the prefailed state, the rock fabric is well cemented, and microcracking is limited in extent. Creep can occur under constant stress, increasing stress, and decreasing stress. All creep laws in Tables B-1, B-2 and B-3 have been derived for this state.

In a failed rock, creep rates will be larger than for the unfailed rock at the same stresses. In addition, stable creep can occur only under a decreasing stress (Cogan, 1978) because creep strains bring the rock rapidly toward the stress-strain failure line. Once the failure line is reached, total collapse of the sample will occur. Failed rock conditions are common underground in both pillars and opening walls. In most cases these rocks are stable for long periods of time because rock stresses decrease as the strains increase.

B.4 CREEP FUNCTIONS FOR SALT

Various combinations of the functions $f_1(t)$, $f_2(\sigma)$ and $f_3(T)$ have been used to define creep in salt beds. These relationships between strain, time, stress, and temperature are

$$\epsilon = A \ \sigma^a \ T^b \ t^c$$ (Lomenick and Bradshaw, 1969; Starfield and McClain, 1973)

$$\epsilon = B \ \sigma^d \ \exp(-\Delta H/kT) \ t$$ (Carter and Heard, 1970)

Equation (B-1) describes primary creep only and was derived from laboratory stress-strain tests upon model pillars made of salt. Equation (B-2) describes secondary creep only and was derived from laboratory tests on numerous samples tested at a variety of stresses and temperatures.

B.5 CREEP LABORATORY TESTING

Laboratory testing includes uniaxial testing and triaxial testing with heating. Uniaxial tests can produce only the time-temperature dependence of strain for the uniaxial stress conditions. Triaxial tests can yield the full time-temperature-confining stress dependence.

To determine all the parameters--such as those in Equations (B-1) and (B-2)--required to describe rock creep, extensive testing is required. A series of constant-temperature-and-confining-stress creep tests can be performed in a triaxial testing machine. For each test, a series of constant axial loads is applied to a rock core initially placed under constant temperature and constant confining pressure acting radially upon the sample. The resulting strain-time curves can be used to derive the time law. For Equation (B-1), a plot of $\ln \varepsilon$ vs. $\ln t$ yields a straight line, the slope of which is the parameter c, the intercept $\ln A$. From this series of tests, a second plot, ε vs. σ can be made for each axial load σ for a specific time period after loading. For Equation (B-1), the slope of the plot of $\ln \varepsilon$ vs. $\ln \sigma$ will yield the parameter a.

Next, the temperature can be changed and the procedure repeated, thereby obtaining new values for c, A and a. For a given confining pressure, several runs at different temperatures will yield a relationship between strain and temperature. In Equation (B-1), the slope of a plot of $\ln \varepsilon$ vs. $\ln T$ will yield the parameter b. For Equation (B-2), the slope of a plot $\ln \dot{\varepsilon}$ vs. T^{-1} will yield $-\Delta H/k$ and, since k is known (Planck's Constant), the activation energy, ΔH, is obtained.

Because of the time involved to perform all of these tests described above, it can be seen that a determination of all the creep parameters for all the rocks at a particular repository site may not be feasible. Testing programs designed to determine orders of magnitude of these parameters, and the boundaries above and below which they do not occur, can be devised to reduce testing requirements.

For a particular repository site, laboratory testing can be used to identify the best functional relations suitable for developing a full-scale equation describing primary and secondary creep behavior of the salt and its associated rocks. This testing should take into account the environment that will exist at all locations within a particular repository. The physical parameters to be measured will be

For Eq. (B-1): A, a, b, and c

For Eq. (B-2): B, d, and ΔH.

For an actual rock, the stress dependence may be the same for primary and secondary creep, and in that case, a = d. Similarly, for limited temperature ranges, the exp ($-\Delta H/kT$) term may be replaced by a term T^b, the same temperature dependence term as in Eq. (B-1).

APPENDIX C
THERMAL PHENOMENA
AND PARAMETERS

C.1 THERMAL PHENOMENA

Heat Transfer

The three generally accepted mechanisms of heat transfer are conduction, convection, and radiation. Each mechanism can act independently or in combination to produce a flow of thermal energy between one part of a medium and another, or across the surfaces of contact between two media. Heat flow occurs from regions of higher temperature to ones of lower temperature.

Heat flow by thermal conduction occurs between neighboring regions which have different temperatures. Since molecular activity is a function of temperature, molecular vibrations are more intense in the hotter than in the cooler regions. Through a process of collision between molecules as in a gas, or between free electrons as in a metal, energy is transferred to the cooler regions.

The flow of energy by conduction is expressed by the following law of heat flow

$$\frac{dq}{dA} = k\frac{dT}{dx} \qquad \text{(C-1)}$$

where dq/dA is the heat flow rate across a unit area dA (Btu/ft^2-hr), dT/dx is the thermal gradient between two points on either side of the area through which the heat is flowing ($^{\circ}$F/ft), and k is the thermal conductivity (Btu/hr-ft-$^{\circ}$F).

Heat flow by thermal convection is the transfer of thermal energy by the actual physical movement of heat from one location to another by an intermediate substance in which thermal energy is stored. For example, heat can be removed from hot rock around a tunnel by the ventilation system. Air at low temperature is forced down the tunnel and comes into contact with the hot rock walls. By a combination of conduction processes and radiation processes at the air-rock boundary, thermal energy is transferred to the air. The flowing air then stores that energy and removes it from the tunnel to the outside atmosphere.

The basic equation for heat flow from the rock to the air is governed by the relation

$$q = Ah\,(T_s - T_f) \qquad \text{(C-2)}$$

where q is the heat flow (Btu/hr) across a boundary area A (ft^2), T_s the solid surface boundary temperature (^oF), T_f the ambient fluid temperature (^oF) and h the heat transfer coefficient (Btu/hr-ft^2-^oF).

The heat transfer coefficient h is composed of conduction and radiation portions. The conduction portion includes heat flow from the rock wall through the fluid boundary layer, and into the turbulent flow zone. The thermal conduction thus depends upon the viscosity and thermal conductivity of the fluid within both the boundary zone and within the mass of flowing fluid. It also depends upon the creation of heat by fluid friction within the fluid itself.

Heat transfer by radiation is the transfer of energy between bodies by electromagnetic energy. Every material emits electromagnetic waves which can be absorbed by other materials. The emission of energy leads to a decrease in temperature, while the absorption of energy leads to an increase in temperature.

A body that absorbs or emits all electromagnetic energy is called a black body. Most solids are opaque and absorb or emit electromagnetic radiation only upon a thin surface layer, so that heat transfer by radiation within the material is not significant. However, solid surfaces can emit and absorb radiation from the air, or through the air to and from other solid surfaces. Thus, heat transfer by radiation can occur between hot repository walls and between these walls and the ventilation air.

The basic equation for heat transfer by radiation is

$$q = AF \sigma (T_1^4 - T_2^4) \qquad \text{(C-3)}$$

where q is the heat flow (Btu/hr), A is the area of one of the surfaces (ft^2), σ is the Stefan-Boltzmann constant (0.171×10^{-8} Btu/hr-ft^2-$^oR^4$), T_1 and T_2 the absolute temperatures ($^oR = {}^oF + 460$) of the two bodies, and F is a geometric factor dependent upon the configuration of the two bodies.

If one of the bodies is ventilation air and the other tunnel wall rock, then

$$q = A \epsilon_w (T_w^4 - T_a^4) \qquad \text{(C-4)}$$

where T_w is the wall rock absolute temperature, T_a the ambient air absolute temperature and ϵ_w the emissivity of the rock wall.

Emissivity is the ability to emit thermal radiation. It is based upon Stefan's law that the amount of radiant energy emitted from a body is dependent only on the fourth power of its absolute temperature. For a perfect emitter, the black body,

$$E_b = \sigma T^4 \qquad \text{(C-5)}$$

where E_b is energy in (Btu/hr-ft^2). For a real body, less emission occurs than for a black body, and this property is measured by the emissivity parameter

$$\epsilon = \frac{E}{E_b} \qquad \text{(C-6)}$$

so that

$$E = \epsilon \sigma T^4$$

where E is the rate of energy emission per unit area of the real body and ϵ is its emissivity.

Transient Heat Flow

Transient heat flow occurs when the temperatu of a region within a solid changes with time. This change with time is governed by the Fourier Equation, written here in one dimension:

$$\frac{k}{wc} \left(\frac{\delta^2 T}{\delta x^2} \right) = \frac{\delta T}{\delta t} \qquad \text{(C-7)}$$

where k is the thermal conductivity (Btu/hr-ft-^{0}F)

w the weight density of the material (lbf/ft^3)

c the thermal capacity (Btu/lb-^{0}F)

T temperature (^{0}F)

x distance (ft)

t time (hr).

The term k/wc is called the diffusivity, K.

In any medium where temperature is a function of time as well as location, transient heat flow effects will occur. If a tunnel in a repository has no air flow through it, the air temperature in the tunnel will become equal to the rock temperature. If, after a period of time, ventilation is reintroduced, cool air will pass down the tunnel and pick up heat from the wall rock. The amount of heat gained will decrease with the distance of flow because, as the air temperature rises, the temperature difference between the air and the rock ($T_w - T_a$) decreases. With time, more and more heat will be removed from the rock, and an annulus of cooled rock will develop around the tunnel perimeter. Eventually, a state of equilibrium will be reached in which the heat flow into the air will be balanced by the heat flow into the cooler annulus from warmer rock deeper in the tunnel walls. The temperatures within the walls will then increase from a value just above air temperature to ambient rock temperature at some point deep in the wall rock. The rate at which the annulus of cooled rock will develop will depend upon rock diffusivity. The final shape of the temperature distribution within the wall rock will depend upon rock conductivity.

Thermoelastic Phenomena

When a rod of metal is heated, the length of the rod increases, the increase being proportional to the change in temperature:

$$\frac{\Delta \ell}{\ell_o} = \alpha \, \Delta T \qquad \text{(C-8)}$$

where $\Delta \ell$ is the change in length (ft), ℓ_o the original length (ft), ΔT the change in temperature (^oF), and α the coefficient of thermal expansion.

To prevent any change in length, a stress equal to

$$\sigma = E \frac{\Delta \ell}{\ell_o} \qquad (C\text{-}9)$$

would have to be applied to the bar, where E is the elastic (Young's) modulus (psi). Substituting the value of $\Delta\ell/\ell_o$ in Eq. (C-8) into (C-9), one obtains the relationship between stress and temperature:

$$\sigma = E \alpha \Delta T \qquad (C\text{-}10)$$

Thus, changes in temperature can lead to changes in stress. Within a repository, heat will raise the temperature of the rocks, and the rocks will expand. Restraints on rock movement can retard free expansion, so that rock stresses in a repository will increase.

Thermochemical Phenomena

As the temperature of a rock is increased, its physical state will change. These changes will be reflected in their physical properties. Some of these changes can be brought about by temperature-induced chemical changes such as

- Vaporization of pore water
- Vaporization of water of hydration from individual minerals
- Phase changes in individual mineral crystals
- Oxidation of chemicals within the rock
- Melting of isolated minerals
- Surface tension effects and the relaxation of grain boundary stresses.

Since these changes can affect rock properties, especially strength and creep rates, a knowledge of their existence and of the temperature at which they act is desirable.

Thermomechanical Phenomena

Changes in rock temperature always result in changes in rock physical properties. Every physical property is affected to a different degree. The identification of those physical properties that change significantly within the range of repository temperatures is desirable. Significant changes will affect the stress distribution and heat flow pattern within the repository. Important properties to consider are rock strength, elastic moduli, thermal conductivity, thermal capacity, emissivity, diffusivity, thermoelastic constants, plastic yield stress, creep parameters, porosity, and permeability.

Some influences of temperature upon salt properties are

- Decrease in strength with rising temperature (Dreyer, 1977)
- Strong decrease in thermal conductivity with rising temperature (Birch and Clark, 1940)
- Strong increase in creep rates with increasing temperature (Lomenick and Bradshaw, 1965).

C.2 THERMAL PARAMETERS

In order to evaluate and monitor the thermal state of a repository in bedded salt, the thermal parameters of the associated rocks must be known. The capabilities to measure these must exist for both in-situ and laboratory conditions. The main thermal parameters of interest are

- Temperature (T)
- Thermal Conductivity (k)
- Thermal Capacity (c)
- Diffusivity (K)
- Heat Transfer Coefficient (h)
- Emissivity (ε)
- Heat Flow Rate (q)
- Thermoelastic Constant (α)
- Thermochemical Properties
- Thermomechanical Properties

Temperature (^{0}F)

Temperature is a measure of the relative thermal state of a body in relationship to a standardized body called a thermometer. If a thermometer is placed in contact with a body, it will either gain or lose heat until it reaches thermal equilibrium with that body; at that point, the temperature of the thermometer is said to equal that of the body.

Thermal Conductivity (Btu/hr-ft-^{0}F)

Thermal conductivity is a measure of the amount of heat that flows through a unit of surface area per unit time given a temperature gradient at the surface. It is the property of the material that determines the rate of heat flow through the material when subjected to a thermal gradient.

If a heat-producing canister is surrounded by a rock with a low thermal conductivity, the flow of heat away from the canister and into the rock will be slower than if it were surrounded by a rock with a high thermal conductivity. In other words, temperature rise within a canister and surrounding rock will vary inversely with thermal conductivity. The lower the conductivity, the higher the temperature.

In addition, different rocks have different thermal conductivities; heat flow within the repository will be controlled partially by these differences. For example, if a set of canisters is placed in a salt bed of high thermal conductivity, which is bounded by shale beds of low conductivity, a greater heat flow will tend to move radially outward into the salt rather than vertically into the shales. This condition will influence temperature distributions in the repository. For purpose of reference, some thermal conductivity values are listed below.

TYPICAL THERMAL CONDUCTIVITIES
AT 68^{0}F (unless otherwise noted)

Material	Thermal Conductivity (Btu/hr-ft-^{0}F)[1/]	Reference
Copper	223	(Geidt, 1957, p.358)
Steel (C ≈ 1%)	25	(Geidt, 1957, p.357)
Rock Salt	0.66 - 1.74	(Clark, 1966, p.464)
Rock Salt [2/]	3.56	(Heard, 1979, p. 37)
Shale	1.00 - 1.38	(Clark, 1966, p.462)
Water	0.344	(Clark, 1966, p.482)
Dry Soil	0.08 - 1.33	(Clark, 1966, p.479)
Air	0.0148	(Geidt, 1957, p.358)

1/ Conversion factor: Btu/hr-ft-^{0}F = 0.004136 cal/s-cm-^{0}C

2/ Measured at 95°F and 1500 - 5800 psi confining pressure

Thermal conductivity of rock is dependent upon mineral content, porosity, the type of porosity, the type of pore fluid, the degree of saturation, external applied stress, and temperature. In general, the thermal conductivity of a rock sample will

- Decrease with an increase in the degree of internal cracking
- Decrease with a decrease in water content
- Increase with an applied external stress
- Decrease with an increase in temperature (but there are exceptions)
- Decrease with a change in porosity configuration from vugular to fractured.

The heat flow across pores within a rock is reduced by open, flat cracks, but the application of external stresses closes these cracks and thus increases conductivity (Walsh and Decker, 1966). The removal of water from the pores introduces air which has a lower conductivity than water (Clark, 1941); thus, heat flow across the pores (or crack) is retarded and the conductivity decreases. The worm-hole nature of vugular pores does not affect conductivity as much as flat cracks because the heat can flow easily around pore openings through mineral material (Walsh and Decker, 1966). An increase in temperature strongly decreases conductivity in many rocks, including salt (Birch and Clark, 1940). Finally, under high external pressures, fractures and joints close, and the thermal conductivity of a fractured rock approaches the intrinsic conductivity of the rock matrix for both dry and saturated rocks (Walsh and Decker, 1966).

From the above discussion, it can be seen that laboratory-determined conductivity can differ from in-situ conductivity because of different states of stress, porosity, and water content. For the purposes of analyzing heat flows in a repository in bedded salt, in-situ conductivity measurements are recommended.

Thermal Capacity (Btu/lb-^{o}F)

Thermal capacity is the amount of heat required to raise a unit of mass of homogeneous material one degree in temperature.* Thermal capacity is also a rock property that varies with rock type. It has an influence upon the heating and cooling rates of rocks during transient temperature changes as noted in the subsection entitled Diffusivity, p. C-12. Some typical values of thermal capacity are listed below.

THERMAL CAPACITY FOR VARIOUS MATERIALS

Material	Thermal Capacity (Btu/lb-^{o}F)	Reference
Copper	0.0915	(Geidt, 1957, p.357)
Steel	0.113	(Geidt, 1957, p. 357)
Rock Salt	0.19-0.47	(Dames and Moore, 1978, p. A-13)
Coarse Earth	0.44	(Geidt, 1957, p. 357)
Water	1.00	(Geidt, 1957, p. 357)
Air (@ 70^{o}F)	0.24	(Geidt, 1957, p. 357)

Heat Transfer Coefficient (Btu/hr-ft^{2}-^{o}F)

As described earlier, the heat transfer coefficient is composed of a radiative portion and a convective portion. For heat transfer from a rock tunnel wall to ventilation air, radiative heat transfer will dominate at higher temperatures, e.g., 500^{o}F and higher, but at lower temperatures, heat transfer by conduction between the rock and air will also be important.

* Specific heat is the (dimensionless) ratio of a material's thermal capacity to that of water at 59^{o}F (15^{o}C); numerically, specific heat equals thermal capacity.

Equation (C-2) could also have been written as

$$h = h_r + h_c = \frac{q}{A\,(T_s - T_f)} \qquad \text{(C-11)}$$

where h_r is a radiative heat transfer coefficient and h_c a convective coefficient. The radiative coefficient can be derived from the radiation law using known emissivities and tunnel geometry, or from measurements in tunnels.

Determination of the conductive heat transfer coefficient is complicated by air flow conditions. All ventilation air flow is turbulent, so that a fluid boundary layer develops at the rock surfaces. This layer will vary both in thickness and in configuration with the air velocity. Since heat transfer by conduction across the layer depends upon fluid viscosity, eddy current conditions, frictional resistance in the air and other factors, the estimation of heat transfer coefficients is difficult. Suitable values can be generated, but they will vary with air velocity, location, air and rock temperatures, rock surface conditions, and other possible factors.

Diffusivity (ft^2/hr)

Diffusivity (K) is defined as the thermal conductivity (k) divided by the product of the weight density (w) and the thermal capacity (c), or

$$K = \frac{k}{wc}$$

Diffusivity is a convenient combination of two other thermal properties, and therefore not an independent parameter.

Diffusivity is used in heat transfer calculations involving non-steady-state conditions--i.e., conditions in which boundary temperatures change with time. It is a measure of the heat storage capacity of a body under changing temperature conditions. For any heat flow calculations made for conditions of changing rock temperatures, the diffusivity must be known.

Weight Density (lbs/ft^3)

Density is the mass per unit volume for a material. Weight density is the weight per unit volume in lbs/ft^3. Some typical weight densities are

Copper	559 lbs/ft^3	(Geidt, 1957, p. 357)
Steel	487	(Geidt, 1957, p. 357)
Rock Salt	130-152	(Dames and Moore, 1978, p. A-2)
Water	62.4	

Emissivity (Dimensionless)

Emissivity is the ratio of the radiation emitted by a surface to the radiation emitted by a perfect black-body radiator at the same temperature. Emissivity is a measure of the radiant heat flow that can occur at a rock-air interface. This parameter will play a role in the heat transfer between rock faces and the air in the ventilation system. It will be a function of rock type and rock surface conditions.

Heat Flow Rates (Btu/ft^2-hr)

Heat flow rates are the amounts of heat flow across a surface of unit area per unit of time. They are not measured directly but must be calculated from temperature measurements.

Thermoelastic Constants (in/in-^{o}F)

For rocks, the relative change in volume with change in temperature is normally anisotropic--i.e., the change in length will differ in different directions. For bedded salt strata, the thermoelastic strains measured parallel to bedding will differ from those measured perpendicular to bedding. The thermoelastic constants will vary with temperature, but the variation should be small. In order to calculate thermal stresses induced by temperature increases, the thermoelastic constants of the strata are required. Some typical values are

Rock Salt - 20 to 22 x 10^{-6} in/in-^{o}F (Dames and Moore, 1978)

Limestone - 14.4 x 10^{-6} in/in-^{o}F (Clark, 1966)

Thermochemical Properties

Thermochemical changes within a rock are identified by measuring the release or absorption of heat associated with a change in temperature. For example, the evaporation of pore water will be accompanied by the absorption of heat. For each change, a heat of activation (H_A) associated with the change and the temperature (T_A) at which it occurs, serve to identify the phenomenon.

If a thermochemical change adversely affects rock strength or some other property, the activation temperature at which the change occurs can serve as a limiting temperature above which rock temperatures should not rise. The identification of adverse effects requires testing.

Thermomechanical Properties

Thermomechanical properties will be measures of the temperature effects upon rock properties. These can be graphs or tables showing the property as a function of temperature, equations that relate the property to temperature, or indices that relate property changes to temperature.

In most cases data are lacking that could be used to introduce thermomechanical factors into the analysis of instrument data. For example, rock strengths as determined in the laboratory at room temperature can be used to design openings at room temperature. But to this date, there are no techniques that allow the prediction of rock strength, for example, at 300°F without laboratory testing at 300°F.

The same situation obtains for thermal conductivity measurements made at room temperature: heat flow calculations will not accurately predict actual heat flow in rocks at 300°F. For salt, the conductivity decreases strongly with temperature rise, so that heat flow rates will be lower and repository temperatures will be higher than predicted by room-temperature conductivities.