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NEW DEVELOPMENTS IN MEASUREMENTS
TECHNOLOGY RELEVANT TO THE STUDIES OF DEEP
GEOLOGICAL REPOSITORIES IN BEDDED SALT

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ABSTRACT

This report presents new developments in measurement technology relevant to the studies of deep geological repositories for nuclear waste disposal during all phases of development, i.e., site selection, site characterization, construction, operation, and decommission. Emphasis has been placed on geophysics and geotechnics with special attention to those techniques applicable to bedded salt. The techniques are grouped into sections as follows: tectonic environment, state of stress, subsurface structures, fractures, stress changes, deformation, thermal properties, fluid transport properties, and other approaches.

Several areas that merit further research and developments are identified. These areas are: in situ thermal measurement techniques, fracture detection and characterization, in situ stress measurements, and creep behavior. The available instrumentations should generally be improved to have better resolution and accuracy, enhanced instrument survivability, and reliability for extended time periods in a hostile environment.

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1. INTRODUCTION

The purposes of this report are to survey new developments in measurement technology relevant to studies of deep geological repositories for nuclear waste disposal, to evaluate their limitations and potential, and to identify areas which require further research and development efforts. The extent to which a deep geological repository is effective in containing nuclear waste will be controlled by the physical and chemical characteristics of the geological environment where a repository is located. The dimensions of the area to be studied vary from large tectonic settings to the surfaces and microcracks; and the time span ranges from instantaneous response to the study of long-term properties for tens of thousands of years. Furthermore, thermal and radioactive loadings to a repository will present new challenges to the site selection, and the design, development, and operation of a repository which no engineering undertaking has ever met. Therefore, a large number of diversified techniques will be required, with strict demand for instruments with better resolution and accuracy, and reliability for extended time periods in hostile environments.

An extensive bibliographical search as well as numerous interviews with manufacturers, suppliers, professionals, and organizations currently working in the area of instrumentation development have been conducted. The authors' attendance at technical meetings and workshops has also generated useful leads and information.

The techniques described in this report are grouped into sections: tectonic environment, state of stress, subsurface structures, fractures, stress changes, deformation, thermal properties, fluid transport properties, and other approaches. Emphasis has been placed on geophysical and geotechnical techniques with special attention to those applicable to bedded salt. All the techniques described have been developed recently or are under current development. As a result, there is little available information on instrument performance, potential, and limitations. The level of detail used to discuss each technique as well as each section varies throughout the report. This variation is also attributed to the differences in the availability of pertinent information.

Uncertainties of measurement techniques are very difficult to assess in general terms because the measured results are usually medium and environment dependent. The fact that most geological materials are heterogeneous and/or anisotropic makes the assessment even more difficult. One approach to this problem is to measure the same parameter using different techniques. Consistent data from different techniques should add confidence in the results. Comparisons of these types are included wherever available.

There are several special measurement problems for the bedded salt. Salt has low strength and high creep potential, particularly at elevated temperatures. Instruments designed for in situ measurements such as stress and deformation have to take creep properties into account. Salt brines are highly corrosive and may reduce the useful life of instruments. The fact that salt is a good

transmitter of electromagnetic waves makes radar a very promising tool for salt exploration.

The report is intended to complement the International Engineering Company report (IECU, 1979), prepared for LLNL, "Review of Geotechnical Measurement Techniques for a Nuclear Waste Repository in Bedded Salt" which represents a state-of-the-art review of available techniques. Relevant conclusions drawn by the IECU report are:

- Geophysical measurement techniques are mainly exploratory in nature and should be correlated with geological data in order to increase confidence in the results.
- It is now possible to measure underground stresses, stress changes, rock elastic properties, and rock deformation. Instruments that will operate reliably at high temperatures need to be designed, especially for stress-change monitoring and deformation measurements.
- Thermal measurement techniques are not well developed. No techniques are available to measure the emissivity or heat transfer coefficients of rocks underground.
- Research and development are required in the areas of rock fracture evaluation and the effects of stress on permeability.

Additional research and development recommendations made by other knowledgeable instrumentation specialists such as those in the GAIN report (1978) and the Holzer and Ramspott report (1979), as well as those made by the authors of this report, are also included.

II. TECTONIC ENVIRONMENT

Deep geological repositories for nuclear waste must be located in a region where earthquake hazard and other tectonic activities will be limited for a period of time of ten to hundreds of thousands of years. Therefore an understanding of the tectonic setting of a potential repository site is an important step of the site selection process. Very few techniques have been developed in this area recently. However there are several projects under the Regional Neotectonic Analyses Program (U.S.G.S., 1979a) which may produce new techniques and approaches for the studies of regional seismic activity.

- Regional Neotectonic Analyses Program :

The modern instrumental record of earthquake history is too short to assess long-term regional seismicity. The spatial and temporal distribution of Holocene faults should furnish valuable information on past activity and provide a base for future extrapolation. The Regional Neotectonic Analyses Program sponsored by the U.S.G.S. (1979a) supports evaluations of seismic and tectonic potentials in the near (10^2 years) and distant (10^6 years) future throughout the country. Projects supported by FY 1980 include (U.S.G.S., 1979b), for example, "Subsurface mapping of bedrock structures of Hayward Fault zone: a feasibility study," (University of California, Berkeley), "Recurrence intervals on Pleito Thrust Fault, Transverse Ranges, California," (Foothill-de Anza College District), "Aspects of the Holocene history and behavior of San Andreas Fault system," (California Institute of Technology), "Paleomagnetic dating of late Neogene deposits in the

Atlantic Coastal Plain with application to date tectonic deformation, Southeastern U.S.," (Columbia University), and "Fault scarp morphology: indication of paleoseismic chronology," (University of Cincinnati). This program apparently points the right direction and will encourage the development of new techniques and approaches to seismic prediction (U.S.G.S., 1979b).

- Deep Crustal Structures:

Deep seismic reflection surveys carried out by the Consortium for Continental Reflection Profiling (COCORP) revealed major structures within the continental crust in a variety of tectonic settings across the U.S. (Schilt et al., 1979). The VIBROSEIS technique (Fowler and Waters, 1975), developed by the Continental Oil Company, was used in all surveys. When combined with other geological and geophysical studies, COCORP is a powerful technique for obtaining a much more detailed knowledge of the continental crust and its evolution. Features such as faults, magma bodies, unconformities, plutons, and the crust-mantle transition zone with dimensions as small as a few kilometers can be detected. This is a considerable improvement over the conventional seismic reflection technique.

An artificial shear wave source is being tested as an exploration tool (Schilt et al., 1979). If proved feasible, the ability of reflection profiling to identify magma bodies would be greatly enhanced. This is

due to the fact that shear waves cannot propagate through a liquid, thus, a stronger reflection signal would be generated at the boundary of the magma body.

The causes of long term tectonic instability are often deep rooted. Therefore, a detailed knowledge of the deep crustal structure will contribute much to the understanding of the long term stability of a region.

The ability to predict long term regional stability is strongly dependent on how well we understand the pattern of past activity in the region and its present tectonics. Therefore, researches in the areas of subsurface mapping of bedrock structures, recurrence interval of faults, and techniques for dating tectonic deformations are all very important. The projects under the Regional Neotectonic Analyses Program are still in progress and no information on their outlook is available at this time. However, further research in these areas should be continued.

The deep reflection survey technique described above is a very powerful tool. The results obtained from these surveys should be combined with those obtained from the Continental Scientific Drilling Program C (U.S. Geodynamics Committee, et al., 1979) to construct the deep crustal structures.

Tectonic environment is an important subject which has also been intensively studied by earth scientists as related to earthquake hazard reduction and in

energy related fields. Large manpower and heavy financial support are required to carry out these types of large scale research. close cooperation with other earth science communities is most appropriate and highly desirable.

III. STATE OF STRESS

The absolute state of stress in a rock mass is of fundamental importance to deep geological repositories because it affects the mechanical stability of the repository as well as the physical properties of the rock mass. A variety of techniques for determining in situ stresses in rock mass have been developed, but the results from different techniques often show large discrepancies. There are two major reasons for these discrepancies. First, in all cases the stress state is deduced from an observable effect of stress change such as elastic wave velocities, resistivity, strain, and fluid pressure necessary to hold open a fracture. Uncertainty about the complexity of the relationship between the stress and the observed effect, and simplification of this relationship are the obstacles to the development of a reliable technique (GAIN, 1970). Secondly, every element of rock in the earth is simultaneously subjected to a number of different stresses such as natural overburden stresses, tectonic stresses caused by geologic forces outside of the immediate area, induced stresses arising from stress concentrations around openings, as well as from thermal effects, and residual stresses resulting from changes in stress history. The measured stress is the cumulative effect of all the above sources which may vary from point to point (IECO, 1979).

Two types of techniques are commonly used for the measurement of absolute state of stress in rock masses, the stress relief method and the hydro-fracturing method. In the stress relief method a portion of the stressed rock is cut free by overcoring. The strain or deformation changes that are induced by overcoring or some other form of stress relief is then measured and the

original state of stress is calculated from the moduli of the rock and the amount of deformation measured. In the hydrofracturing technique, a section of the borehole is packed-off and fluid is injected into the pack-off section to initiate fracture. The state of stress is then deduced from the fracture orientation and the amount of fluid pressure necessary to keep the fracture open. Both types of measurement techniques have been around for some time, but improvements as well as new variations have been made recently. A new approach to infer the state of stress by measuring the ultrasonic wave velocities in a borehole is also included.

- Strain Relaxation Techniques:

Engelder and Spar (1978) made a comparison of three strain relaxation techniques, i.e., surface overcoring, the doorstopper, and the U.S.B.M. borehole deformation gauge, to investigate the influence of residual strain on stress measurements. A brief description of these techniques can be found in the IECO report (1979). Their discussion indicates that the precision of strain relaxation measurements is seldom better than 20% in magnitude and $\pm 10^\circ$ in orientation, and that there are distinct differences among the three techniques. Surface overcoring is most sensitive to residual strains relative to the borehole deformation gauge. These inherent differences are unlikely to be resolved in the near future.

A method to measure the total stresses in an isotropic elastic medium by measuring radial displacements of the periphery of the hole before and after another hole with a larger radius is drilled parallel to the

measurement hole was proposed by Akinov et al. (1974). The technique uses the principle of stress concentration effect due to an opening and the stress relief due to an adjacent hole. It is a variation of the conventional stress relief method but has the advantage of not requiring the drilling of a core. The estimated error of this method is 15-20% due mainly to uncertainty in the elastic moduli of the rock mass. This method should be used in conjunction with other techniques.

The stress relief method can only be used on the surface or at shallow depths. The measured result generally only represents a local value which may be strongly affected by local stress concentrations.

Redundant measurements are highly recommended. Although this type of measurement has been commonly used in competent rocks, special care should be taken when it is applied to bedded salt because of the creep property of salt.

- Hydrofracture Technique:

Hydraulic fracturing is the only technique used to measure the state of stress in situ directly. It is also the only currently available way to determine stresses at depths greater than 70 m in a borehole. The U.S.G.S. hydraulic fracturing project (Zoback, 1978) demonstrated that a great deal of information on the physical state of materials at depth (up to 230 m in his case) can be gathered through an integrated series of borehole measurements. The accuracy of the hydrofracturing technique was estimated to be 5-10% for minimum stress and 25% for maximum stress (Holzer and Ramspott, 1979). This technique may not be

particularly suitable for bedded salt because of the high solubility of salt in water, but it should be very useful for crystalline rocks and other geological media. It has the further advantage that the measured stresses represent the average values of a region rather than a point. More research to improve the understanding of the controlling factors in fracture initiation and fracture propagation in anisotropic media is recommended.

- ultrasonic Spectroscopy:

Research in ultrasonic spectroscopy for the purpose of in situ stress measurement was initiated by the Bureau of Mines (Aggson, 1976). It is based on the principle that stress induced velocity anisotropy in rock is a function of the applied stress. A feasibility study of a borehole stress measuring device based on ultrasonic spectroscopy is currently in progress at LLNL. This technique is not limited in depth and does not require the time-consuming processes of overcoring or grouting. However, the calculated stress depends not only on the measured velocities but also on the initial velocity anisotropy (unstressed) and on the rate of change of this anisotropy to stress. Possible ways to obtain these data are by measuring these parameters on core samples in the laboratory or by measuring these parameters in situ under various fluid pressures in a packed-off section of the borehole.

Since this technique is still under development, not much information is available. A prototype borehole tool is scheduled to be built in FY 82.

Techniques for in situ stress measurements definitely need improvement. This is particularly true for deep boreholes. Simplicity of the relationship between stress and the observed effect is a desirable feature of any potential method. The ideal in situ stress measurement technique would be a wireline tool capable of operating in both deep and shallow boreholes. Deep-hole measurements would be extremely valuable in the planning stages of a repository development. For both overcoring and hydrofracturing techniques, significant objections can be raised with respect to the validity of the simplifying assumptions made in interpreting results of measurements. As mentioned before, the hydrofracturing technique may not be suitable for bedded salt. This is also true for the overcoring technique because of the creep behavior of salt. Ultrasonic spectroscopy appears to be a promising technique and deserves further research.

The uncertainty involved in the hydrofracturing technique was estimated to be 5-10% for minimum stress and 25% for maximum stress, and that for the overcoring techniques was about 20%. Whether the accuracy of these techniques is adequate or not has to be answered through sensitivity analysis provided by the modeling efforts.

IV. SUBSURFACE STRUCTURES

Subsurface structure is one of the major factors to be considered for the selection of a repository site. Subsurface structure will affect the design of a repository and the containment characteristics of a repository site. Undetected subsurface structural features in the vicinity of a repository could imperil the performance of a repository. Various techniques can be used to determine these subsurface structures with varying degrees of success. Surface measurement techniques (e.g., seismic reflection profiling) have the advantage of being relatively inexpensive and can easily cover a large area in a nondestructive, nonpenetrating way. Underground measurement techniques generally have better resolution and accuracy than surface techniques because of their closer proximity to the area of interest. Underground techniques can be used in single or multiple boreholes, and also along tunnels and exploratory adits.

Geophysical measurements used to infer subsurface structures often require considerable interpretation. Therefore they may be heavily influenced by the assumptions used. In many cases, more research and development are needed in the areas of data processing and analysis. On the other hand, redundant measurements of the same parameters using different techniques coupled with direct borehole data should be able to produce a consistent structure model. Another important principle is learning while exploring. In other words, the information obtained from measurements should be fed back to update the measurement strategy.

A variety of techniques will be described below. Some of them have not yet been tested in the field, so it is difficult to assess their potential and limitations. The fact that salt is a very good transmitter of electromagnetic waves makes radar a very promising tool for salt exploration.

- High Resolution Seismic Reflection:

The standard seismic reflection technique is generally used for a reconnaissance survey of a large area. Recent developments in recording instrumentation and data processing have improved the resolution of this technique, permitting the location of faults having less than 3 m of displacement (Farr, 1979a) and the resolution of a 3 m thick bed at a depth of 3,000 m (Farr, 1979b). The high resolution of this technique is achieved by using a small charge to produce a high frequency signal and by using a new detector which measures ground acceleration rather than velocity, as well as by improved data processing and analysis. The limitation in resolution of this technique, at present, depends on how much high frequency signal can be retained and on how well the velocity structure of the area is known.

The seismic reflection technique can be used to cover a large area in a nondestructive way. It should be extensively used to gather as much information as possible before any borehole is drilled, and the data should be reanalyzed in conjunction with the borehole data when they are available.

- Borehole Antenna for Electromagnetic Waves:

Many borehole instruments require antennas for transmitting and receiving electromagnetic signals. Present borehole antennas can only radiate a broad beam of electromagnetic energy and, therefore, are not suitable for determining the azimuthal direction to the point of interest. Lytle and Laine (1978) have reported a preliminary design of a miniaturized directional antenna which could radiate a narrow beam of energy and be useful in determining the azimuthal direction to any anomaly of interest. This concept is currently being actively developed. Such an antenna may be useful in locating and estimating the size and depth of salt cavities by using only one borehole for transmitting and receiving. However the efficiency of the system has not been fully evaluated. The trade-off between the beam angle and transmitted energy may require that the system be used as a receiver only.

- Borehole Gravimeters:

Borehole gravimeters are relatively new instruments used to measure the mean density and porosity of rocks; these measurements can also be used to infer the presence of some types of subsurface structures such as salt cavities. Borehole gravimetry is a unique well logging method because it is sensitive to conditions far from the borehole. However, structures inferred from gravity measurements are not unique.

Therefore, this technique should be used together with other techniques. Hearst (1977) has developed some formulae that identify

the locations in the subsurface to which a borehole gravimeter is most sensitive. This information can be used in developing a measurement strategy to select the optimum spacing between gravimeter stations to investigate any location of interest. Schmoker (1979) has published some results which also should aid in enhancing the quality of borehole gravimetry data. He investigated the accuracy and precision of borehole gravity data when using a LaCoste-Romberg borehole gravimeter. His results indicate that the likelihood of poor gravity measurements increases sharply for vertical intervals longer than 50 m and increases approximately linearly with increasing time between readings. Schmoker also found that, for station intervals of 23 m or less and when the time between readings is less than 18 minutes, the gravity difference between two points can be measured to $\pm 10 \mu$ gals.

- Horizontal Exploratory System:

The exploration of a candidate repository site will require that several vertical boreholes be drilled. The number of vertical holes drilled has to be kept to a minimum so that the containment ability of the site will not be imperiled. Therefore, a measurement system to produce maximum information from each borehole is highly desirable. Rubin et al. (1979) have recently concluded a feasibility study and design of a new borehole instrumentation system that may produce adequate data along a long horizontal borehole drilled parallel to the tunnel axis for site evaluation. The system consists of a highly mobile package that includes radar, a pulsed acoustic system and

resistivity measurements using variable spacings. This technique may be useful as a precursor to the construction of pilot tunnels. It may reduce accidents, and may help determine whether the construction of a pilot tunnel is feasible or whether the site merits further exploration.

- Cross-Hole Measurement System:

Cross-hole measurements can be used to measure fractures as well as many other features. These measurements involve the use of more than one borehole; transmitters and receivers are emplaced within separate boreholes, and signals are transmitted across the rock mass. One limitation of this approach is that it lacks sufficient resolution to detect and distinguish all the features which may affect the transmitted signal. A series of articles by Lytle and his colleagues at LLNL (Lytle 1978, Lytle, et al. 1978a, 1978b) details a system which greatly increases the resolution of cross-hole measurement techniques. Using this system, the transmission properties of a subsurface region are sampled by sending a continuous electromagnetic signal between a transmitter and a receiver in different boreholes. From the network of sampled signals, which vary according to the electrical properties of the materials through which they pass, the region's properties can be reconstructed in fine detail. This system has been field tested and an excellent correlation was found between the predicted and encountered subsurface geologic structure and fracture density. This technique can be applied with seismic or electromagnetic signals and may be applicable in locating, among other things, abandoned adits, brine pockets, breccia pipes and solution cavities in salt.

- Acoustic Holography:

The use of tunneling machines as a viable excavation method for constructing a repository is being actively considered. Tunneling machines, which may measure over 7 m in diameter and cost over one million dollars, are the equivalent of a large drill. When broken rock, cavities or other changes are encountered unexpectedly, the operation may be brought to a halt, sometimes with the machine being buried under rock debris. Fitzpatrick and Price (1977) have conducted a feasibility study that suggests that acoustical holography technology can be used to allow the machine operator to "see" at least three diameters ahead of the face being excavated. Such a system may make hazardous tunneling conditions less critical, and may reveal any hidden structures in the vicinity of the tunnel.

- Radar Systems:

Ground probing radar is one of the most useful available geophysical methods for salt exploration. A radar system probing into salt will detect discontinuities in the rock material when those discontinuities are represented by changes in the transmission properties (dielectric constant) of the rock, or if the rock remains the same but is filled with water. Several publications have appeared in the literature concerning the use of ground-probing radar (Stewart and Unterberger 1976, Tarantolo and Unterberger 1978a, 1978b, and Unterberger 1974, 1978). Radar systems can detect many types of discontinuities which can affect a repository layer. These include: a) solution cavities in salt, b) dome flanks, c) lenses of anhydrite, shale, sandstone, d)

faults, e) old undetected boreholes, f) fractures in rock. Radar is a geophysical tool which is still being developed and it certainly merits further work.

Wats (1979) of the U.S. Geological Survey (Denver, CO) is conducting research related to radar systems. The objectives of his project are to determine the capabilities and limitations of high frequency radar techniques and to develop and field test prototype equipment. Some measurements of the transmissivity of salt will also be tried so that the scattering properties of salt will be better understood. An adequate understanding of this phenomenon is essential for choosing the optimum operating frequency for a pulsed radar system.

- Sonar System:

In salt or other rocks that contain some moisture, radar waves are highly attenuated so that the range of probing is reduced drastically. Unterberger (1978) reported the development of a sonar system that uses 24 kHz sound pulses. Probing ranges of 400 meters in dry salt and of 215 meters in wet salt have been recorded.

Several recent developments in underground measurement technology have been described, some of them should prove to be useful exploration tools. For the case of bedded salt, radar systems appear very promising and merit further research. The presence of abandoned boreholes within the general vicinity of a repository site can also reduce its radionuclide containment capabilities. The detection of old, uncased boreholes should be of paramount importance

during the site exploration program. Radar systems have been used to detect boreholes in salt environments. However, there is no technique reported in the literature concerning the direct detection of uncased boreholes in salt. Therefore, the area of borehole detection merits further study.

Borehole measurement techniques can also be used to monitor the repository during and after the emplacement of the waste. Systems used for monitoring purposes should be able to operate reliably for extended periods of time under the conditions of an operating or sealed repository. Most of the systems presently available would probably stop functioning after a few years of operation. Hence, considerable research and development effort should be spent to improve the survivability and reliability of borehole instruments. Another problem associated with the use of borehole systems for monitoring is that the instruments and/or the cables used to carry electrical power and signals may compromise the effectiveness of the borehole plug. The development of power packs and telemetry systems that will not compromise the integrity of sealed boreholes is highly desirable (see also Section X).

V. FRACTURES

The detection and characterization of fractures within a rock mass are extremely important to a repository because fractures control the movement of groundwater in the subsurface (see also Section IX) and thus provide potential pathway for radionuclides to escape. Furthermore, the behavior of a large rock mass depends not only on the properties of its constituents, but also on the fractures in the rock mass. Nevertheless, fractures are sometimes difficult to detect and fracture-related properties are often difficult to model. There are several reasons for these difficulties. First, most techniques lack the resolution to detect small fractures more than a few meters away. Secondly, there is, at present, no systematic way to characterize fractures in the rock mass. And thirdly, the mechanism of crack propagation and crack-crack interaction are still not fully understood. Both in situ measurements and laboratory characterizations are important in this respect. Some techniques discussed in Section IV can also be used to detect fractures; several new approaches will be described below.

- Fractures Assessed From Well Log Data:

A new approach for detecting natural fractures was proposed by Gomez-Rivero (1978) using well log analysis. This approach utilizes data from nuclear porosity logs, and deep and shallow resistivity logs. One limit of this approach is that while it detects the existence of fractures, it does not measure fracture characteristics

such as location, orientation, continuity or permeability. However, this approach may serve to cross-check results from other measurement techniques used to detect the presence of fractures.

- Sonic Probe for Fracture Detection:

Sunier et al. (1979) reported the development of a sonic probe measurement technique designed to detect fractures in the subsurface. One advantage of this technique is that it can operate in wet or dry boreholes, whereas several other acoustic borehole techniques are limited by the type of fluid present in the hole. The probe, designed and built by Southwest Research Institute for LLNL, consists of a linear array of seismic sources which send acoustic pulses into the wall of the borehole. The reflected signal from a fracture is then picked up by the receivers and processed. It is expected that the probe will detect existing fractures 10 meters away from the borehole. Results from the initial tests are inconclusive. The technique at present seems quite promising. However, more information from field test is required before a definite assessment can be made.

- Air Injection Techniques:

Stress-induced and blast-induced fractures extending from an underground repository can significantly affect radionuclide containment. The location and extent of these fractures should be determined so that steps can be taken to minimize the fracture effects. Miller et al. (1976) described an air injection technique to

study the extent of fractures around tunnel openings. This technique can only be used qualitatively and does not provide a way of calculating the permeability of the fractures.

- Shear Wave Reflection:

A feasibility study of fracture detection using ultrasonic shear waves was reported by Waters et al. (1978). The laboratory results showed that a shear wave reflection profiling system had successfully detected an irregular crack (either air or water filled) induced within a large Sierran granodiorite specimen. The maximum depth of penetration of the equivalent field system was estimated to be 10 meters in a reasonably unfractured rock mass. The advantage of using shear waves rather than compressional waves is that sharper reflection signal would be detected because shear waves cannot transmit through the air or water. On the other hand, shear waves are more easily attenuated than compressional waves.

- Impedance Camera Technique For Rock Core:

Lytle and Dines (1978) have developed an "impedance camera" for assessing the detailed interior structure of rock cores. The transmission properties of the rock core are sampled by sending and receiving electromagnetic signals across the sample. From the network of sampled signals the properties of the sample can be determined in fine detail. This camera may be used to detect any structure within the sample which may affect any of the laboratory properties being measured. The initial system uses low frequency electromagnetic

probing. Later versions will use microwave, ultrasonic, x-ray, gamma ray and infrared techniques. This concept has also been used to develop a cross-hole measurement system (see Section IV). The laboratory and cross-hole techniques are both under active development.

- Ultrasonic Attenuation Technique:

A new approach using signal averaging and digital processing for measuring ultrasonic attenuation in highly attenuative materials was reported by Sears et al. (1979). Attenuation is calculated from the ratio of spectral amplitudes between the sample and a reference of low dissipation. Samples of polycrystalline NaCl from Avery Island were used to examine the crack density effect on the attenuation of compressional and shear waves. Controlled heat treatment was used to induce thermal cracking for variation of the crack density. This technique may be used for characterization of cracks in core samples. However, the measured results represent the average property of the sample. No information concerning the orientation and continuity of cracks can be derived.

- Cracking Stress:

Heinze (1977) described a laboratory tool for the study of crack behavior in rock. A thin rock wafer (about three times the thickness of a normal thin section) is loaded in sequential increments. Photomicrographs are taken after each increment, then digitized, and the strain and displacement fields for each increment are computed from numerical comparison of the photos. The technique can determine the

local microscopic stresses with sufficient accuracy to estimate the cracking stresses quantitatively. A knowledge of the local stresses is needed to understand the initiation and propagation of microcracks and to construct a predictive model of the brittle deformation of crystalline rocks.

Although we have briefly described a variety of techniques to detect and to characterize fractures, many of these techniques are still under development and have not been fully field tested. Additional research and development efforts will be needed to enhance the capabilities of existing fracture characterization technology. This is particularly true for the instrumentation needed to monitor changes in fracture properties with time and temperature.

Laboratory measurements of fracture-related properties under simulated in situ conditions are very important in providing fundamental information about rock behavior. The size of samples which can be handled by most laboratory apparatus, at present, is limited to 15 cm in diameter. However, small samples do not adequately represent the rock mass which is often affected by many discontinuities and inhomogeneities. Therefore, the feasibility of a large-scale test facility to determine physical properties of large blocks of fractured rock (a sample size of about one meter) at relevant pressure, temperature, and stress conditions should be determined (Holzer and Ramspott, 1979). Another related problem is how to interpret the laboratory data in terms of the in situ conditions. Research and development in this area is also needed.

The available field techniques often lack penetration into the rock mass. Both sonic reflection techniques have an estimated operational range of about 10 m. It would be highly desirable to extend this range to, say five times the diameter of the excavation.

Techniques related to fracture flow will be discussed in Section IX.

VI. STRESS CHANGES

The data obtained from monitoring stress and strain changes in a rock mass as a function of time will be used to assess the stability of a repository, to verify model calculations and to predict future rock behavior. All the techniques used for absolute stress measurements can, in principle, be used for measuring stress change with varying degrees of convenience and reliability. IECU (1979) listed all the available techniques and references for detailed information. Techniques used to monitor stress changes with time for repository applications will have to operate reliably over a long period of time in a hostile environment of high temperature, corrosive agents, and water. Several techniques will be briefly discussed below. However, none of them are specifically designed for repository application. Modifications may have to be made before they can be used. Research and development efforts to increase the reliability of these and other existing techniques are recommended.

- Flatjack:

Terra Tek developed a stress monitoring system by using a water-filled flatjack (Pratt and Hardin, 1978). Since a flatjack is most sensitive to the stress perpendicular to it, three flatjacks are grouted into slots oriented at 120° to each other to determine the orientation of stress. The sensitivity of this stress monitoring system is illustrated by its recording of the typical diurnal and semidiurnal stress changes associated with earth tides which have a strain magnitude of about 3×10^{-8} . A miniaturized version of the stress

meter is being designed to fit a 7.5 cm diameter borehole. For high temperature application (e.g., heater testing), a flatjack filled with mercury instead of water is under development and calibration (Pratt, 1979).

- Vibrating-Wire Gage

Clark (1978) reported progress in monitoring stress changes near active faults in Southern California by using the vibrating-wire stress meter manufactured by IRAD GAGE, Inc. The stress meters are actually rigid inclusion strain gages which measure the stress required to hold a borehole open by exciting the stressed wire across the hole and measuring its period of vibration. The gage can be calibrated accurately in the laboratory and conversion of the reading to an actual stress value is straightforward. The instruments give only the changes in stress level from an arbitrary initial pre-stressed level. Each unit is unidirectional, and measures only normal stress, therefore three gages in different orientations in a plane are required to define the principal stress components in that plane. Heater tests in Stripa granite demonstrated that the IRAD gages require individual calibration at various temperatures (Binnall et al., 1979).

- Monitor Magnetic Field

In a different approach, Tarasov et al. (1976) proposed to monitor changes in the vertical component of the magnetic field as an indicator of changes in the state of stress of the rock mass around an underground opening. This approach is based on the observation that

the intensity of magnetization of magnetite decreases under compression. The method will probably be difficult to apply to studies of weak magnetic rocks such as bedded salt and associated rocks.

- Monitor Seismic Velocities:

The possibility of using the stress sensitivity of seismic wave velocities in the study of stress in the earth's crust has long been discussed by seismologists. For continuously monitoring in situ seismic velocity, the results depend on the type of seismic generator used and on the capability to achieve a high signal-to-noise ratio. Reasenberg and Aki (1974) used an air gun repeatedly shot in a water-filled hole every 6 or 10 seconds to measure the seismic velocity. The variation in velocity correlates well with the variation in tidal stress. Gupta (1973) observed significant premonitory changes in the difference between the two shear wave velocities (acoustic birefringence) for two earthquakes, each of magnitude about 4, in Nevada. Thus, these experiments provide the basis for monitoring in situ stress changes by a precise, continuous measurement of seismic velocities.

The stress change measured using this technique represents the average value between the source and the receiver. For repository application, a scaled down model is needed. Furthermore, the relationship between velocities and stress for each host rock has to be determined in the laboratory.

A different approach, using a continuous wave instead of pulses, is being investigated in the laboratory at LLNL. This technique measures the effect of stress on the phase shift between the initial signal and the received signal due to the time delay of the signal transmission through the sample. Preliminary results indicate that the technique is extremely sensitive and capable of measuring stress changes of 5 to 10 PSI. However, more research is required before its potential can be realistically assessed.

Techniques to monitor stress change play an important role during several repository development stages. No available technique will meet all the requirements for repository application without modification. All the comments and recommendations made in the state of stress section (Section III) can all be repeated here. The creep behavior of salt would affect the measurements even more when strain relaxation techniques or vibrating-wire gages are used because creep itself is a deformation with time under constant stress. Therefore, the measured results cannot decouple creep effects and stress changes. Furthermore, creep will be enhanced as the temperature is increased.

The monitoring of velocity changes, particularly the continuous wave approach, appears to be promising. Its high sensitivity is extremely useful in monitoring not only stress effects but also those due to temperature, fractures (dilatancy or thermal cracking), and pore pressure. Considerable research is required to understand the effects of these parameters so that

they can be determined quantitatively from the measured field data. This technique may also be applied to cross-hole measurements around waste canisters.

VII. DEFORMATION

Deformation is the response of a rock mass to loading. Stress-deformation phenomena can be grouped into four basic ideal mechanical states, i.e., elastic, plastic, creep, and post-failure. Physical properties vary not only with rock type, environment (e.g., pressure and temperature), and fracture history, but also with the type of deformation (IECO 1979). Therefore, deformation is intimately related to the stability of a repository, and results from monitoring deformation could offer clues to the future behavior of the rock mass. There are many techniques designed to measure the deformation or deformability of rock masses. Most of the techniques used to measure stress or stress changes are actually strain measuring devices, thus they will provide information on deformation of rock masses. IECO (1979) briefly discussed all the currently available techniques. A few new approaches will be described below.

There are several areas where improvement in measurements of deformation should be made. First of all, the resolution of some of these techniques needs improvement (e.g., rod extensometer). This may be approached in two ways; by improving the resolution of the calibration procedures and by understanding the inherent differences among different techniques. A common dilemma in measurement technology is either that a device is not sensitive enough to detect the expected change or the sensitivity is so high and the signal is affected by so many factors that the measured data can not be interpreted intelligently. Research and development efforts to enhance interpretation technique are highly recommended.

Another area that needs improvement is the accommodation of the high temperature environment. Most of the techniques are not designed for high temperature operation. Modification or redesign of existing instruments for high temperature operation is urgently needed. (See also Section VIII).

- Optical Diastimeter:

Conventional mechanical extensometers (e.g., rod extensometers) require grouting the anchors to the host rock; thus, potential errors in measured data may be introduced due to anchor creep. This can be a problem particularly at high temperatures. Sampaolo (1977) used a precision diastimeter to measure the convergence of walls in an excavation by comparing the incoming and outgoing polarization phases of a light beam generated by a xenon lamp. The precision of the technique is of the order of 0.1 millimeter. This technique may be useful to monitor rock behavior during construction, and during the heating and cooling phases of the repositories.

- Laser Holography:

Borehole holography to monitor deformation of boreholes is being studied by Spetzler (1979). This technique is based on the observation that fringe patterns between two consecutive exposures of the same hologram on a strained surface can be quantitatively correlated with the amount of deformation. This technique is potentially of high sensitivity. However, more research is required to develop it into a field tool.

- Bubble Tiltmeters:

Tiltmeters can be used to monitor subsidence and ground movements across faults or fractures. In the last few years, two bubble tiltmeters were developed by Rockwell and Kinemetrics. The Rockwell tiltmeter was tested by McConnell (1977) in a borehole in Massachusetts. The initial results show good correlation with earth tides. The Kinemetrics tiltmeter was extensively tested and then discussed in a conference on stress and strain measurements related to earthquake prediction sponsored by the U.S.G.S. (Berger and Wyatt 1978, Bilhaun and Beavan 1978, Harrison et al. 1978, Isacks et al. 1978, Morrissey and Stauder 1978, and Mortensen 1978). The general view of most practitioners is that the instruments are highly stable and sensitive, but that environmental noise is always a problem. However, for monitoring deformation in a deep repository these instruments could be much more reliable provided temperature effects on these instruments can be corrected. More research efforts to improve the interpretation procedure is recommended.

- Borehole Strain Meter:

Sacks (1978) reported the development of a borehole strain meter which consists of a liquid-filled resilient tube. Field test results indicate that the strain meter responds to a variety of disturbances and the intrinsic long-term noise (weeks to years) is very low. The mean difference between the monthly readings of borehole strainmeters and a 100 meter quartz bar extensometer in the same tectonic

environment is of the order of 10^{-7} in strain. The strain meter can detect borehole distortion as small as 10^{-9} mm. This device may be used to measure the time-dependent properties of bedded or domed salt. It may also be used to measure deformation in hardrocks under squeezing ground conditions.

- Acoustic Emission:

The sudden release of elastic energy in a solid material is accompanied by acoustic emission. It has been studied both in the laboratory and in the field, and used as a monitoring technique for mine safety and slope stability (Hardy and Leighton, 1977).

Acoustic emission is generally associated with deformation of brittle materials. Recent studies of acoustic emission in ductile material such as rock salt (Richardson, 1980 and Roberts, 1980) have improved our understanding of the mechanisms of deformation in rock salt. For a single crystal of salt, the acoustic emission rate peak can be correlated with the yield-point. However, for polycrystalline salt there are many possible acoustic emission sources including grain boundary interactions, initiation and propagation of microcracks, and dislocation motions resulting in intragranular slip. The acoustic emission activity resulting from a number of possible source mechanisms gives a much more complex total picture than that of the single crystals (Richardson, 1980). Salt also produces acoustic emission during primary and secondary creep stages when subjected to uniaxial

compression at room temperature. Salt behavior is more ductile at high temperatures and confining pressures and acoustic emission monitoring might provide a means to identify the stresses at which the predominate deformation mechanisms change. Additional experiments on salt under confining pressure and high temperatures are needed to investigate this potential tool (Roberts, 1980).

Meister (1980) reported several case studies of acoustic emission in salt rock as a monitoring system in the field. He observed, in one case, that the high rates of emission represented a critical phase of the thermo-mechanical behavior of salt rock. It is not the magnitude of temperature itself, but that of the temperature gradient which mainly influences the strength of the rock salt. In another case, the sudden lowering of the groundwater table caused a lot of local sink-holes and subsidence. These events produced intensive acoustic emission activity in the frequency range from 600 Hz to 20 KHz. The instruments used in these studies were single channel magnetic recorders with barium-titanate transducers as sensors. Additional research and development efforts to improve the monitoring system are necessary to gain more fundamental knowledge of the acoustic emission phenomenon.

Most of the studies so far are based on information from the acoustic emission rate - number of emissions per unit time. Research efforts in the areas of locating the source, identifying the source mechanism as

well as understanding the relationship between the frequency content of an individual acoustic emission event and other physical properties is recommended.

A variety of techniques have been described above. Most of these techniques are still in the development stage, so we do not have enough relevant information to assess their potential and limitations. For the study of bedded salt basins, those techniques which require grouting will be affected by the creep behavior of salt, and these effects should be accounted for. Optical methods should be relatively free from creep effects and should be suitable for bedded salt.

Acoustic emission appears to be a very useful tool for monitoring some type of deformation during repository construction and operation. However, more research to improve the hardware as well as to understand the fundamental mechanisms is definitely needed.

As with other types of instruments used in a repository, long term reliability in a wet, high temperature environment should always be a major consideration in instrument design.

VIII. THERMAL PROPERTIES

Thermal loading of rock masses is one of the special problems that make a nuclear waste repository different from a conventional underground opening. The main thermal parameters of interest are temperature, thermal conductivity, thermal capacity, diffusivity, heat transfer coefficient, emissivity, heat flow rate, and coefficient of thermal expansion. IECU (1979) has presented brief discussions of all these parameters and available techniques to measure them. Very few new techniques are under development. We will discuss an approach to analyze thermal conductivity data and some results from in situ heater tests. In order to understand the effect of temperature on the performance of a repository, the capabilities to measure these thermal parameters must exist both in the laboratory and in the field. Laboratory measurements under controlled conditions will provide fundamental data on the thermal effects of the rock material while in situ measurements will provide the true response of the host rock mass. In situ heater tests are particularly important because in addition to measuring the response of the rock mass, they also provide a chance to study the performance of the instruments.

For salt, increased temperature will increase the creep rate, induce brine migration, and it may also heal any existing fractures. As mentioned before, it is the magnitude of the temperature gradient rather than the temperature which mainly influences the strength of rock salt. (Meister, 1980).

- Thermal Conductivity:

The thermal conductivity of a rock mass controls the temperature distribution inside the rock mass, and thermal conductivity of a rock mass is controlled by its mineral constituents, texture, structure, and water content. Robertson (1979) made a thorough compilation of available thermal conductivity data for rocks and minerals. He found strong correlations between thermal conductivity and its controlling factors for various types of rocks. The data are presented in graphs showing the effects of porosity, water content, accessory mineral content (e.g., quartz, olivine, and clay), and temperature. The report included rocks such as basalt, granite, limestone, dolomite, sandstone, and shale as well as glasses, quartz, anhydrite, gypsum and salt. Thus, the thermal conductivity of a variety of rocks may be estimated from a few of their characteristics.

- Laboratory Techniques:

Laboratory measurements of thermal properties of rocks at elevated temperatures and pressures will provide fundamental data to model the performance of a repository. LLNL (Ramspott, 1979) is currently testing an experimental apparatus for core samples 13 cm in diameter and 23 cm long. Temperature can be as high as 770°K and confining pressure as high as 200 MPa. The apparatus is unique in the sense that it can be used to simultaneously measure the thermal conductivity,

thermal diffusivity, and coefficient of thermal expansion of candidate waste repository rocks at in situ conditions of temperature, pressure, and fluid content. Samples from the Avery Island salt dome are currently being measured.

- Fluid Temperature Estimation:

Parasnis (1971) presented a simple procedure to calculate the equilibrium temperature in a circulating fluid. Reading time is reduced from 60 minutes to 10 minutes by eliminating the requirement of achieving temperature equilibrium prior to reading. Hanson and Kasameyer (1979) proposed a technique to predict temperature using standard tracer methods. These techniques may be applicable to ground water temperature predictions for water flowing slowly around a repository.

- In Situ Heater Tests:

In situ heater tests in bedded salt, domed salt, shale, granite, and basalt have been completed or are underway. These tests provide experience and vital information about the instruments used as well as the behavior of the rock mass under thermal loading. In general the results of these tests show that valid data can be obtained using modified and calibrated off-the-shelf geotechnical instrumentation. However, the elevated temperatures and the need for long time integrity in a wet environment created many problems. In granite at Stripa, Sweden encountered problems which included: 1) circuit failure due to

water leakage in some thermocouples, most of the horizontal extensometers, and most of the vertical USBM gages; 2) stepwise displacement output from the extensometer due to internal rod friction; and 3) uncertainties of data reduction for the IRAO gages because the gage calibration constants are sensitive to rock modulus and coefficient of thermal expansion as well as to the exact seating of the preloading wedge system (Binnall et al., 1979). The Conasauga near-surface heater experiment in shale (Krumhansl, 1979) also encountered a water problem. Presumably, similar and other problems may be encountered in other heater tests. Therefore, more effort should be applied to the development of instruments to meet the environmental, reliability, and accuracy requirements for monitoring repository performance.

Very few new developments in the area of thermal properties measurement have been described. Some research and development efforts to improve the available laboratory and in situ techniques are being made by several national laboratories. Nevertheless, more efforts are definitely needed. This is particularly true for in situ techniques where no techniques are available to measure emissivity, thermal heat transfer coefficient, or thermal expansion coefficient. (IECO, 1979). The question whether data from the laboratory are adequate or not for these parameters can only be answered by the results of sensitivity studies.

In situ measurements are particularly important because what we are concerned with is the thermal properties of the rock mass not those of the rock materials. For instance, displacements measured from in situ heater tests were found to be smaller than those predicted from model calculations when the effect of fractures was not taken into account.

The state-of-the-art in temperature measuring devices is adequate for repository research as far as the accuracy of the measurement is concerned. However, there is room for further improvement in at least two areas. First of all, experience from in situ heater tests indicated that water leakage caused circuit failure in some thermocouples. The problem may be more severe in a corrosive salt environment. Secondly, the long term stability of these thermocouples has not been established. (Holzer and Ramspott, 1979).

IX. FLUID TRANSPORT PROPERTIES

Fluid flow in fractured rocks is difficult to model, and laboratory experiments often do not represent in situ conditions. However, fluid flow is probably the most important mechanism for radionuclide transport. Thus, a full understanding of in situ permeability and the relationships between permeability and other physical parameters is of ultimate importance. A few new techniques to measure permeability in the laboratory or in the field will be briefly described. We do not intend to cover hydrogeology related subjects in this report other than those limited efforts below.

- Electromagnetic Method:

Lytle et al. (1976) proposed to use an electromagnetic method to monitor the movement of injected fluid in the subsurface. The method could be expanded to measure in situ permeability, permeability anisotropy, and rate of flow. This technique requires the injection of a fluid having a different electrical conductivity from that of the fluid existing naturally in the medium. Electromagnetic waves are used to monitor the rate and direction of flow by measuring the amount and location of change of the electromagnetic signal. Permeability and other parameters can then be calculated from the measured changes. This technique is currently still under development.

- Large Scale In Situ Permeability Measurement:

A novel way to measure large-scale permeability in fractured granite at Stripa was reported by Witherspoon et al. (1979). The technique measures the mass of water removed by the ventilation system within a 30 m long drift sealed off with an impermeable bulkhead. The pressure and temperature in the rock mass surrounding the drift are monitored in packed-off sections of boreholes. When pressure and flow rate have stabilized, macroscopic permeability values can then be calculated. This technique provides a unique way to measure large scale permeability--a parameter required by numerical models of large flow systems (10^9 in³).

- Laboratory Techniques:

Laboratory measurements of fluid transport in low permeability rocks are very difficult and time consuming. Heard et al. (1979) report a system that simultaneously measures permeability, electric conductivity, ultrasonic velocities and strain in igneous and metamorphic rocks. The samples are tested under moderate lithostatic and pore water pressures, at moderate deviatoric stresses and at 25°C. Test samples were 15 cm in diameter by 28 cm long, and both fractured and unfractured rocks were evaluated. The measured data are used to correlate permeability with electric conductivity so that eventually permeability can be estimated from electric conductivity data which are much easier to measure. The correlations are generally very good for fractured rocks. However, more data are required to establish a firm

relationship between them. The effect of stress on permeability was also evaluated. Among the rocks studied, there is a wide range in sensitivity of permeability to stress and pressure, but the effect on each individual sample is relatively small (Trimner et al., 1980).

Large scale in situ permeability measurement is very important because the measured data include the effect of fractures. The technique described above has been successfully used at Stripa, Sweden in fractured granite. However, in order to interpret the measured data intelligently, a full understanding of the effects of other physical parameters such as stress, temperature, and fracture on permeability is ultimately required. Laboratory measurements under controlled conditions should be able to provide the information. Unfortunately our present knowledge of the effects of these parameters on permeability is still quite limited. Further research and development in this area is recommended.

Most rocks are anisotropic and heterogeneous. Thus variation in physical properties among samples is often a rule rather than exception. In addition, physical properties of rock samples are often influenced by previous tests. The laboratory technique described above measures a variety of parameters on one sample simultaneously, so that variation in measured data due to sample difference or sample history is minimized.

X. OTHER APPROACHES

This section includes other techniques or approaches not covered in the categories mentioned before. However, they are individually as important as any other techniques described before.

- Rock Squeeze:

Lee and Klym (1978) suggested that the time rate of swell measured on fresh cores can be used as an index in assessing the susceptibility of underground structures to the adverse effect of rock squeezing. These measurements may also be incorporated into a finite element simulation of rock-structure vs. time behavior around an underground opening. Rock squeeze determinations are particularly important on shales and on sedimentary rocks with shaly interbeds because generally these rocks will be the most susceptible to rock squeeze.

- Borehole Plug Monitors:

D'Appolonia Consulting Engineers Inc. (1979) discussed various types of instrumental systems that can be used to monitor the effectiveness of borehole plugs and shaft seals. Westinghouse Electric Corporation (1976) conducted a feasibility study on the use of borehole systems that minimize the disturbance by the instrument package on borehole plugs and seals. Wireless systems are preferable. These systems employ transmission of either elastic or electromagnetic waves to convey data and/or power between the subsurface instrument packages and the surface with natural earth as the conducting medium.

The effectiveness of borehole plugs and shaft seals is, of course, very important to the containment capability of a repository. Field testing of the wireline systems is required before they can be developed into a true field tool.

- Geostatistic

Kriging is a geostatistical technique for interpolating data which are spatially correlated. Kriging has been successfully used for fifteen years in the mining industry to estimate ore reserves. Doctor (1979) evaluated the potential use of kriging in site selection of a nuclear waste repository. He applied the technique to the study of groundwater elevation and depth of basalt at the Hanford site and concluded that kriging can be useful in producing a realistic contour map of the geological formation (or any other spatially distributed parameters) of a potential repository site with an associated measure of uncertainty (kriging error).

Kriging is used at LLNL to study various geological parameters of the Nevada Test Site (NTS). Preliminary results (Candy/Mao, 1980) indicate that the technique is a very useful tool. It can be used to select the best additional sample locations so that the uncertainty can be minimized. And the new information can be used to update the measurement strategy.

The cross sections of the Paleozoic rock depth at WIS produced by kriging based on borehole data alone agree very well with those interpreted by geologists based on borehole data as well as surface geology, gravity data, and seismic reflection data.

The technique cannot be used indiscriminately. Careful construction of the variogram, a statistical model for the variability of data, is the key to the success of the technique. More research to test the technique by applying kriging to a diversified set of data would improve our understanding of the potential and limitations of the technique.

A few unrelated techniques were described in this section. Kriging has been demonstrated to be a very useful technique for site characterization. However it cannot be used indiscriminately. A knowledge of the characteristics of the input data themselves would definitely be helpful in selecting appropriate preprocessing procedures such as constructing variogram, determining anisotropy and drifting, etc.

CONCLUSIONS AND RECOMMENDATIONS

Several new developments within the area of measurement technology have been described. These techniques can be used to measure tectonic settings, rock properties, subsurface geologic structures, stress, strain, thermal properties and fluid transport properties. The systems listed can be used at the surface, underground, or in the laboratory. Many of these techniques may prove to be very useful for the exploration and monitoring of suitable repository sites in bedded salt basins. Several areas which merit further research and development work have been identified. Neither the listing of recent developments nor the listing of suggested research areas should be considered all-inclusive since additional search efforts are still being conducted.

The majority of the recently developed or commercially available techniques were developed to meet the needs and requirements of specific industries (mining, petroleum, construction industries, for example). Many of the exploration and monitoring tools needed for the study of nuclear waste repository sites can be adapted from commercially available instruments. However, several of the techniques that will eventually be included in the list of techniques to be used will have to meet additional requirements not currently met by the commercially available instrumentation systems. These requirements include better resolution and accuracy, enhanced instrument survivability and reliability for extended time periods, and instrument reliability in the presence of thermal and radioactive fields. Several specific measurement areas also merit additional research, development, and improvement.

In order to ensure that the additional measurement systems needed to explore for, characterize, and monitor deep geologic repository sites will be available, several areas that merit significant research and developmental efforts are proposed below. Some of these proposals concern specific measurement techniques which have not been developed or which merit further development. Other proposals suggest that general areas of measurement such as in situ thermal measurements be developed further.

Some of the instruments that will be used to monitor the repository may have to be emplaced in boreholes that need to be permanently sealed. Instruments used in this manner will have to operate reliably for extended time periods, depending upon the monitoring needs. Some of these instruments may be required to function for periods of at least tens of years. The majority of the instruments available will probably operate reliably for only a period of a few years at most. Therefore, it is recommended that techniques that may be used from plugged boreholes be identified and that these be developed further to enhance their survivability and reliability. Other problems and recommendations can be associated with the use of instrumentation systems within sealed boreholes. These include the development of power packs and telemetry systems that will not compromise the sealing effectiveness of the plug(s) within a borehole. Further study and development is also advisable for those techniques that can be used to monitor the effectiveness of a borehole plug.

Borehole techniques as well as techniques used within the rooms of a repository may be used to monitor the repository after the nuclear waste has been emplaced. These instruments will be subjected to heat and radiation fields which may have deleterious effects on their durability or reliability. The effect of heat and radioactivity on monitoring instruments subjected to these fields is also an important area that should be studied.

Old, abandoned boreholes are often present in bedded salt basins. The locations of many of these holes may not be known. These boreholes need to be detected so that their effects on the containment capability of a repository can be minimized. Radar has already been used to detect cased boreholes within salt pillars. However, there is no technique reported in the literature concerning the direct detection of uncased boreholes. The detection of uncased boreholes is another area within the measurement technology field which deserves further study and development.

Radar can also be used to detect and locate many other features which may affect the behavior of a repository. It is probably one of the most useful techniques available for the exploration of suitable sites in bedded salt basins. Radar is clearly a very promising technique that should be developed further.

Acoustic emission measurements appear to be useful in monitoring any mechanically unstable areas surrounding a repository. Acoustic emissions are currently used to locate and qualitatively identify areas of instability.

This measurement technique can be used to monitor a repository from boreholes that would not intersect the repository. It could be used to monitor the repository during the emplacement and decommissioning phases of development without reducing significantly the containment capabilities of the repository. Research in acoustic emission should be directed towards understanding the significance of the content of the emitted signals and, towards improving the ability to locate the source of emission.

There are a few other areas which merit general improvement. The area of in situ measurements of thermal parameters requires significant research and development work. There are no in situ techniques available to measure emissivity, thermal heat transfer coefficient, or thermal expansion coefficient. (International Engineering Company, 1979).

Another general area for improvement is that of in situ stress measurements. In situ stresses are very important because they directly affect the stability of the rock mass surrounding a repository. A few recommendations can be made concerning these measurements. The available techniques for in situ stress measurements, with the exception of the hydrofracturing technique, can only be used to depths of several tens of meters. The development of a technique that could be used to measure stress at greater depths and along a single borehole, prior to the construction of exploratory shafts and tunnels, is very desirable. The development of a stress gage that can function reliably at high temperatures is also recommended. A high temperature stress gage can be a useful tool during heater tests conducted as part of the site character-

ization plan, and as a monitoring tool after waste emplacement has occurred. International Engineering Company (1979) has also made some worthwhile recommendations concerning in situ stress measurements. They suggest that a probe that can make stress determinations in soft and fractured rocks be developed. Soft sedimentary rocks may be associated with salt in bedded salt basins.

The detection and characterization of fractures in the subsurface is clearly of paramount importance when characterizing candidate repository sites. This general area of measurement is still in an embryonic stage of development. Therefore, it is recommended that this area be given prompt attention and that a major research and development effort be directed towards improving the state of the art of fracture detection and characterization.

To improve our understanding of the behavior of salt and other rocks under conditions similar to those existing around repository horizons, a few new pieces of laboratory apparatus should be developed. The capacity to test meter-sized samples that contain fractures is necessary to adequately understand rock mass behavior at depth. Very few facilities which can handle large samples are currently operational and none of them have provisions for high temperature measurements. (Holzer and Ramspott, 1979).

For the case of bedded salt, the understanding of creep behavior is very important to adequately design, construct and operate a repository. The procedures followed when studying creep behavior in the laboratory should be

standardized so that a better understanding of creep phenomena can be achieved. Emphasis should be placed on the study of creep behavior at high temperatures.

The use of geostatistical techniques will also be a very valuable addition to the overall measurement strategy plan. The kriging method, for example, can be used to interpolate between points when sufficient data are not available. This method can also be used to estimate the error associated with interpolation. The error estimate can be used to decide where additional information would be most useful to reduce the interpolation error to an acceptable level. One advantage of this analysis would be that the likelihood of drilling unnecessary boreholes would be minimized. Further study of the kriging method applied to the site selection of deep geological repositories is highly recommended.

REFERENCES

1. Aggson, J. R., "The potential application of ultrasonic spectroscopy to underground site characterization," 48th Annual Meeting of Society of Exploration Geophysicists, San Francisco (October, 1978).
2. Akinov, V. S., Kuksin, V. S., Kurlenga, M. V. and Leont'ev, A. V., "A Method for Determining the Total Stresses in Solid Rock from the Disturbance to the Stress Field Near a Borehole with a Deformeter," Soviet Mining Sciences 10 (1), 10 (1974).
3. Berger, J., and Wyatt, F., "Some Remarks on the Base Length of Tilt and Strain Measurements," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Prediction, U. S. Geological Survey (September, 1978).
4. Bilham, R., and Beavan, J., "Tilt Measurements on a Small Tropical Island," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Prediction, U. S. Geological Survey (September, 1978).
5. Binnall, E., DuBois, A. and Lingle, R., "Rock Instrumentation Problems Experienced During In-Situ Heater Tests," in Proceedings, Symposium on the Scientific Basis for Nuclear Waste Management, November 27-30, 1979, in print (1979).

6. Candy, J. and Mao, N., "Optimal Contour Mapping: A Spatial Estimation Approach," in print, 1980.
7. Clark, B. R., "Progress in Monitoring Stress Changes Near Active Faults in Southern California," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Prediction, U. S. Geological Survey (September, 1978).
8. D'Appolonia Consulting Engineers Inc., "The Status of Borehole Plugging and Shaft Sealing for Geologic Isolation of Radioactive Waste," Battelle Memorial Institute, Report No. ONW1-15 (1979).
9. Dobecki, T. L., Lysne, P. C., and Vittitae, C. N., "Advanced Logging and Formation Evaluation," on Enhanced Gas Recovery Program, Third Annual Report, D. A. Northrop and C. L. Schuster, Editors, SAND-79-0056 (50), (1979).
10. Doctor, P. G., "An evaluation of kriging techniques for high level radioactive waste repository site characterization," Battelle Pacific Northwest Lab, PNL-2903 (1979).
11. Engelder, T., and Sbar, M. L., "A Comparison of Three Strain Relaxation Techniques in Western New York," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Prediction, U. S. Geological Survey (September, 1978).

12. Farr, J. B., "Very High Resolution Seismic Profiling," Preprint Western Geophysical Company, Houston (1979a).
13. Farr, J. B., "Seismic Resolution as a Function of Depth," Western Geophysical Company, Houston (1979b).
14. Fitzpatrick, G. L., and Price, T. O., "Acoustical Holography Goes Underground," Opt. Spectra 11 (9), 57 (1977).
15. Fowler, J. C. and Waters, K. H., "Deep crustal reflection recording using "VIBROSEIS" methods--a feasibility study," Geophysics, 40, 399-410 (1975).
16. GAIN, "Geotechnical Assessment and Instrumentation Needs for Nuclear Waste Isolation in Crystalline and Argillaceous Rocks," Symposium Proceedings, July 16-20, 1978, Berkeley, CA, (1978).
17. Gomez-Rivero, O., "The F-O-m Cross-Plot - A New Approach for Detecting Natural Fractures in Complex Reservoir Rocks by Well Log Analysis," SPWLA Nineteenth Annual Logging Symposium, 1 (1978).
18. Gupta, I. N., "Premonitory Changes in Shear Velocity Anisotropy in Nevada," in Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System, Editor, R. L. Kovack and A. Nur (1973).

19. Hanson, M., Personal Communication, (1979).
20. Hanson, J., and Kasameyer, P. W., "Predicting Production Temperatures Using Tracer Methods," Attachment I, Internal Memorandum, LLL, (1979).
21. Hardy, H. R., Jr., and Leighton, F. W., (Editors), Proceedings of First Conference on Acoustic Emission, "Microseismic Activity in Geologic Structures and Materials," Series on Rock and Soil Mechanics 2, Trans. Techn. Publications, (1977).
22. Harrison, J. C., De Moy, J. M., and Meertens, C., "Tiltmeter Results from Adak," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Prediction, U. S. Geological Survey (September, 1978).
23. Heard, H. C., Trimmer, D., Lin, W., Duba, A., and Bonner, B., "Simultaneous Measurements of Permeability, Electrical Conductivity and Ultrasonic Velocity in Igneous and Metamorphic Rocks," EOS Trans. Am. Geophys. Union 60, 381 (1979).
24. Hearst, J. R., "On the Range of Investigation of a Borehole Geovimeter," Preprint UCRL-81294 (1977).

25. Heinze, W. D., Distortion Measurement Between Photographic Images: A New Rock Mechanics Tool, Texas A&M, Ph.D. Dissertation, (1977).
26. Holzer, F., and Ramspott, L., (Editors), Proceedings of a workshop on thermo-mechanical modeling for a hardrock waste repository, June 25-27, 1979, Berkeley, CA, p. 135, (1979).
27. International Engineering Company, "Review of Geotechnical Measurement Techniques for a Nuclear Waste Repository in Bedded Salt," UCRL-15141 (1979).
28. Isacks, B. L., Hade, G., Campillo, R., Bevis, M., Chinn, D., Dubois, J., Recy, J., and Saos, J., "Measurements of Tilt in the New Hebrides Island Arc," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Prediction, U. S. Geological Survey (September, 1978).
29. Kasameyer, P. W., Personal Communication (1979).
30. Krumhansl, J. L., "Final Report: Conasanga Near-Surface Heater Experiment," Sandia Lab., SAND 79-1855, (1979).
31. Lee, C. F., and Klym, T. W., "Determination of Rock Squeeze Potential for Underground Power Projects," Engineering Geology 12 (2), 181 (1978).

32. Lytle, R. J., "Geophysical Characterization Using Advanced Data Processing," Preprint UCRL-81294 (1978).
33. Lytle, R. J., and Dines, K. A., "An Impedance Camera: A System for Determining the Spatial Variation of Electrical Conductivity," Lawrence Livermore Laboratory, Rept. UCRL-52413.
34. Lytle, R. J., Laine, E. F., Lager, D. L., and Davis, D. T., "Cross-Borehole Electromagnetic Probing to Locate High-Contrast Anomalies," Preprint UCRL-79272, Rev. 2 (1978).
35. Lytle, R. J., Dines, K. A., Laine, E. F., and Lager, D. L., "Electromagnetic Cross-Borehole Survey of a Site Proposed for an Urban Transit Station," Lawrence Livermore Laboratory, Rept. UCRL-52484 (1978).
36. Lytle, R. J., and Laine, E. F., "Design of a Miniature Directional Antenna for Geophysical Probing from Boreholes," IEEE Transactions on Geoscience Electronics (GE-16), 304 (October, 1978).
37. McConnell, R. K., Personal Communication (1977).
38. Meister, D. (1980), "Microacoustic Studies in Rock Salt," Proc. Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, (Ed. Hardy, Jr., H. R. and F. W. Leighton), 259-273.

39. Miller, C. H., Cunningham, D. R., and Cunningham, M. J., "An Air Injection Technique to Study Intensity of Fracturing Around a Tunnel in Volcanic Rocks," Bull. Assoc. Eng. Geol. 11 (3), 203 (1974).
40. Morrissey, S., and Stander, W., "Tiltmeter Research at New Madrid and at Adak: The Stability and Reliability of Shallow Borehole Tiltmeters," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Predictions, U. S. Geological Survey (1978).
41. Mortensen, C. E., "The Analysis of Tiltmeter Data," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Prediction, U. S. Geological Survey, (September, 1978).
42. Parasnis, D. S., "Temperature Extrapolation to Infinite Time in Geothermal Measurements," Geophys. Prospec. 19, 612 (1971).
43. Pratt, H. R., Personal Communication (1979).
44. Pratt, H. R., and Hardin, E. H., "The Terra Tek Stress Monitoring system: Theory, Calibration and Data from the Palmdale Area, California and Salt Lake City, Utah," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Prediction, U. S. Geological Survey (September, 1978).

45. Ranspott, L. D., (ed.), "Waste Isolation Projects: FY 1978," Lawrence Livermore Laboratory, Rept. UCRL-50050-78 (1978).
46. Reasenber, P., Aki, U., "A Precise, Continuous Measurement of Seismic Velocity for Monitoring In-Situ Stress," J. Geophys. Res., 79, pp. 399-406 (1974).
47. Richardson, A. M. (1980), "Using AE Techniques in Laboratory Investigations of Salt Behavior," Proc. Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, (Ed. Hardy, Jr., H. R. and F. W. Leighton), 63-77.
48. Roberts, D. A., "Measuring Acoustic Emission from Salt during Creep," Proc. Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials (Ed. Hardy, Jr., H. R. and F. W. Leighton), pp. 79-86.
49. Robertson, E. C., "Thermal Conductivities of Rocks," U. S. Geological Survey Open File Rept. 79-356 (1979).
50. Rubin, L. A., Fowler, J. C., Griffin, J. N., and Still, W. L., "A New Sensing System for Pre-excavation Subsurface Investigations for Tunnels in Rock Masses," FHWA-RD-77-10 (1977).

51. Sacks, I. S., "Borehole Strainmeters," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Prediction, U. S. Geological Survey, (September, 1978).
52. Sampaolo, A., "Electro Optical Convergence Measurements in Large Underground Chambers," International Symposium on Field Measurements in Rock Mechanics - Zurich, 611 (April, 1977).
53. Schilt, S., Oliver, J., Brown, L., Kaufmann, S., Albaugh, D., Brewer, J., Cook, F., Jensen, L., Krumhansl, P., Long, G., and Steiner, D., "The Heterogeneity of the Continental Crust: Results from Deep Crustal Seismic Reflection Profiling Using the Vibroseis Technique," Rev. Geophys. Space Phys, 17, (1979).
54. Schmoker, J. W., "Accuracy of Borehole Gravity Data," Geophysics 43 (3), 538 (1978).
55. Sears, F., Bonner, B., and Carroll, M., "Ultrasonic Attenuation Measurements in Polycrystalline NaCl Using Signal Averaging and Digital Processing," EOS, Transaction AGU, 60, (1979).
56. Spetzler, H., Personal Communication (1979).
57. Stewart, R. D., and Unterberger, R. R., "Seeing Through Rock Salt with Radar," Geophys. 41 (1), 123 (February, 1976).

58. Suhler, S. A., Peters, W. R., Shroeder, E. C., and Owen, T. E., "Modular Borehole Seismic Reflection Probe," final technical report and instruction manual, Southwest Research Institute, San Antonio, TX, (1979).
59. Tarantolo, P. J., and Unterberger, R. R., "Successful Testing of a 300 Hz Radar Probing System in Dry and Wet Salt," Preprint of paper presented at the 48th Annual International Meeting of the Society of Exploration Geophysicists, San Francisco, California (October, 1978).
60. Tarantolo, P. J., and Unterberger, R. R., "Radar Detection of Boreholes in Advance of Mining," Geophysical Prospecting, 20 (2), (1978).
61. Tarasov, B. G., Dyrdin, V. V., and Ivanov, V. V., "Monitoring the Mechanical State of the Rocks by Means of Changes of the Vertical Component of the Magnetic Field," Soviet Mining Sciences 12 (7), (January/February, 1976).
62. Trimmer, D., Bonner, B., Heard, H. C. and Dupa, A., "The Effect of Pressure and Stress on Water Transport in Intact and Fracture Gabbro and Granite," UCRL-83932, in press.
63. Unterberger, R. R., "Radar and Sonar Probing of Salt," Fifth International Salt Symposium, Hamburg, Germany (1978).

64. Unterberger, R. R., "A Laser for Probing Salt," Fourth Symposium of Salt, Northern Ohio Geological Society, Vol. 2 (1974).
65. U.S. Geodynamics Committee, et al. (1979), Continental Scientific Drilling Program, Washington, D.C. National Academy of Sciences.
66. U. S. Geological Survey, "Regional Neotectonic Analyses," Document for Request for Proposal (RFP) 665W (1979a).
67. U. S. Geological Survey, The Earthquake Hazards Reduction Program, Document for Request for Proposal (RFP) 781W, (1979b).
68. Waters, K. H., Palmer, S. P., and Farrell, W. E., "Fracture Detection in Crystalline Rock Using Ultrasonic Shear Waves," Lawrence Berkeley Laboratory LBL-7051, (1978).
69. Wats, Ray, Personal Communication (1979).
70. Westinghouse Electric Corporation - Advanced Energy Systems Division, "A Systems Analysis of Instrumentation for In-Situ Examination of Rock Properties," Report Y/OWI/SUB-76/99096 (1976).

71. Witherspoon, P. A., Wilson, C. R., Long, J. C. S., Galbraith, R., Gale, J. E., and McPherson, M., "The Role of Large-Scale Permeability Measurements in Fractured Rock and Their Application at Stripa," in Proceedings, Symposium on the Scientific Basis for Nuclear Waste Management, November 27-30, 1979, in print, (1979).
72. Zoback, M. D., "Measurement of In-Situ Stress, Natural Fracture Distribution and Fracture Permeability in a Well Near Palmdale, California," Proceedings of Conference VII - Stress and Strain Measurements Related to Earthquake Prediction, U. S. Geological Survey (September, 1978).