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**Critical Parameters and Measurement Methods for
Post Closure Monitoring: A Review of the State of
the Art and Recommendations for Further Studies**

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CRITICAL PARAMETERS AND MEASUREMENT METHODS FOR POST CLOSURE MONITORING

A Review of the State of the Art and Recommendations for Further Studies

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Summary

Both NRC and EPA regulations require programs of post closure monitoring "to detect substantial and detrimental deviations from expected performance" (EPA 40 CFR 191.14). The unexpected in this case would involve anomalous stress changes that might rupture the cannisters or changes in the hydrologic regime that might accelerate corrosion. In the event of leakage brought about by any means transport of radionuclides to the accessible environment could occur through unexpected changes in the hydrologic flow regime caused either by the long term effects of the thermal loading by the waste or by changes in regional stress or hydrology.

Studies of performance confirmation have identified six parameters or conditions that should be monitored that are associated with the thermal, mechanical and hydrologic phenomena introduced by the waste heat: temperature, stress, displacement, pore pressure, groundwater velocity and permeability. Since it is the thermal load that continues to increase after decommissioning, and which continues to alter the stress field and the hydrological regime, these same six parameters remain the critical ones in post closure monitoring.

At two of the repository sites fractures have been clearly shown to be critical in modelling and performance confirmation; at the tuff site fluid saturation is also a critical parameter and for all the sites estimates of the groundwater velocity through the site are very important. Changes in fracture properties, saturation and fluid flow are thus of continuing importance in post closure monitoring.

Performance confirmation under the conditions extant up to decommissioning can be done with in-situ direct measurements. After closure, access is prohibited and measurements must be made from outside the repository. Post closure monitoring will thus rely in large part on indirect methods in which physical properties that can be measured externally must be interpreted in terms of the parameters and behavior of interest within the repository.

The parameters that can be measured which have a direct relationship to the required critical parameters are:

- (1) near surface temperature
- (2) near surface gas monitoring
- (3) ground surface deformation
- (4) regional and local horizontal strain fields
- (5) near surface microseismic monitoring of displacements at depth.

Parameters that can be measured that have an indirect or interpretable relationship to the required critical parameters are:

- (1) hydraulic head or fluid potential in shallow holes
- (2) electric streaming potentials
- (3) microgravity
- (4) seismic wave velocity and attenuation
- (5) electrical conductivity

Of all the methods that can be used in post closure monitoring, seismic and electrical methods appear to have the most potential and to have received the least consideration. Both are known to be sensitive to the fracture content and distribution, to changes in the stress level in fractured rock, and to fluid saturation.

Post closure monitoring with any of the methods depends on measuring changes in parameters or conditions after excavation and emplacement of the waste. If a program of post closure monitoring is to be undertaken it is essential that measurements begin immediately at the three sites so that there will be a base line of data against which unexpected or significant changes can be detected.

Section 1

Review of Critical Parameters and Available Monitoring Methods

1.1 Introduction

The program of performance confirmation up to the stage of decommissioning is designed to assure that the repository is performing as predicted, or at least is performing within limits that satisfy the established containment criteria. Since subsurface processes that are initiated by the excavation of the repository, and the heat released by the nuclear waste will continue long beyond the retrievability period there will always be some uncertainty about the future performance of the repository. Also, the decision to issue a licensing amendment will be based on a probabilistic analysis in which, by definition, there is always some chance of an unexpected event or development. Common sense, or perhaps simple curiosity, suggests that monitoring for the unexpected is a prudent activity, especially if it is of reasonable cost, easy to implement for future generations, and poses no threat to the integrity of the repository.

In the current regulations the NRC (48 FR 28205) has not emphasized post decommissioning monitoring on the basis that it would not add significantly to the performance assessment, that the prospect of any reliable measurements over a period of centuries was unlikely, and that any effective techniques would probably violate the integrity of the repository.

Nonetheless in a later section, 46 FR 13971, dealing with licensing, NRC indicates that a program of post decommissioning monitoring of the repository must be included within the application by DOE for the license amendment.

The EPA is somewhat more specific in 40 CFR Part 191.4 stating that "(b) Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardize the isolation of the wastes and shall be conducted until there are no significant concerns to be addressed by further monitoring."

It is clear that post decommissioning monitoring as an activity cannot be classed with performance assessment since the latter has to be completed before a decision can be made to issue the license amendment to decommission. The methods for such monitoring are, however, the same as those used in performance assessment with the exception that methods that require access by conduit or drill hole to the repository must be eliminated. No method can be used which could make a path for radionuclides to escape from the repository.

Our task has been to determine which parameters describing a repository could reveal unexpectedly poor performance and which of these could be monitored from outside the repository without violating its integrity. The search has required a thorough review of performance assessment plans and, because of the second restriction, has concentrated on what most of the reports refer to as secondary or indirect measurement techniques. In this process we have discovered that many of these techniques would be very useful in performance assessment itself. They have not received the same consideration as the direct in-situ measurements since before decommissioning direct access to the repository is possible.

A mined geological repository is simply an underground excavation in which containers of radioactive waste are placed and later permanently sealed by appropriate backfilling. What makes the process different from anything ever done before is that the waste containers generate a great deal of heat and that the contents, should they leak, are highly toxic and must not reach the accessible environment. Successful burial implies first that the containers are not likely to rupture due to stresses arising from rock deformation, and are not likely to corrode in the fluid environment, and that, if either of these things did happen, the radionuclides could not be transported away from the site to the accessible environment in a time small compared to several times their half lives. In rock the only significant transport process is by solution in the groundwater so beyond the engineering details of the container and its immediate vicinity, the hydrologic regime and its modification by the heat source are of critical importance.

How the rock in the repository will react to excavation and waste emplacement is predicted using models of the site. In these models the response of the rock (e.g., rock deformation, temperature, fluid motion etc.) is calculated for given properties or parameters of the rock (e.g., rock moduli, thermal conductivity, hydraulic conductivity, etc.). The physics and mathematics of these models are well understood; what gives rise to errors or mistakes in the predicted behavior of the site are errors in the parameters used in the calculation.

Parameter estimation is a key feature of the site characterization. The parameters are then used in the models to predict the repository performance. The waste is then emplaced and the repository response monitored. If the response is as predicted the performance is said to be confirmed and the site can be permanently closed.

This simple scenario is fraught with many practical difficulties. The major one is that the rock mass is not homogeneous and that the parameters can be expected to vary widely throughout the site. The measurement of a parameter must be done on a sample of the rock, or in-situ, so continuous sampling for these measurements would result in unacceptable perforation of the site. This is a classic example of how the complete characterization of an object would destroy the object. The entire problem is now reduced to one of getting 'good enough' parameter values at a 'limited' number of points so that the models will yield 'reasonable' estimates of performance. An equal problem is that of selecting monitoring measurements, again limited in space, that would "assure" that the predicted performance was in fact being realized. Final decisions about performance will have to be cast in a probabilistic framework.

A great deal of thought, analysis and experiment has been devoted to what is essentially a sampling and instrumentation problem. We have reviewed this literature to determine the critical parameters, and the measurement techniques used to measure them, with the special objective of identifying those which could be used in monitoring post decommissioning performance.

1.2 Reports on Critical Parameters and Performance Monitoring

We reviewed bibliographies of reports on each of the major sites: tuff, basalt, and salt. From these we identified reports dealing especially with critical parameters and performance monitoring. Three major reports exist which, in total, give an excellent review of the critical parameters and the current state of the art methods that are available to measure them.

The major reports we have reviewed are:

- (1) Evaluation of Geotechnical Surveillance Techniques for Monitoring High Level Waste Repository Performance. NUREG/CR-2547 (1982) prepared by C. M. St. John, J. R. Aggson, M. P. Hardy, G. Hocking. (JFT Agapito and Associates).
- (2) In Situ Tests Programs Related to Design and Construction of High Level Nuclear Waste (HLW) Deep Geologic Repositories Vol. I and II (1983) NUREG/CR-3065 prepared by W. Roberds et al. (Golder Associates).
- (3) Critical Parameters for a High Level Waste Repository. Vol. I: Basalt (1985) Vol. II: TUFF (1987) NUREG/CR-4161. Vol. III: SALT (1987) NUREG/CR 4161 Prepared by: Vol. I - E. P. Binnall, H. A. Wollenberg, S. M. Benson, L. Tsao, O. Weres. A. L. Ramirez, G. A. Armantrout. Vol. II - E. P. Binnall, S. M. Benson, L. Tsao, H. A. Wollenberg, T. R. Tokunaya, E. M. Didwall. Vol. III - E. P. Binnall, H. A. Wollenberg, S. M. Benson, L. Tsao, E. M. Didwall.

We will refer to these by the above numbers, (1), (2), and (3).

Each of the three major reports have approached the issues in a slightly different manner because the objectives in each were slightly different.

Report (1) ".....recommends geotechnical monitoring programs for evaluation of high level nuclear waste repository performance".

Report (2) is devoted to recommending tests to be used in in-situ test programs (that are expected to be presented in SCR's and includes matching the tests to information needs). An overall objective is:

“To enable the focused, adequate review by NRC of aspects related to design and construction of an in situ test facility and final geologic repository, as presented in U.S. Department of Energy (DOE) Site Characterization Reports (SCR)”

“To ascertain that the DOE site characterization will provide, as far as possible, all the information necessary to permit a review to be conducted by NRC of a License Application (LA).”

Report (3) addresses critical parameters specific to tuff and basalt repositories. This report, while emphasizing the relationship of the physical properties to repository performance, also describes in detail current measurement technology and limitations.

We have attempted to review critically these reports and extract from them methods that would be satisfactory for post closure monitoring. Such methods are mentioned in some of them but, in general, most assume that surveillance will cease after decommissioning.

Report (1) selected six conditions or responses associated with thermal, mechanical and hydrologic phenomena which must be monitored:

Temperature

Stress

Displacement

Pore Pressure

Groundwater velocity

Permeability

The relevance of these parameters to repository performance is detailed, expected ranges are presented and measurement techniques on various time and dimension scales are presented.

In Report (2) key issues relating to performance criteria are laid out in a matrix chart with characteristics (parameters) and relative importance of each parameter to each key issue is coded in the “matrix Table” ES-1 in Appendix II. The key issues

are constructibility, thermal response, mechanical response, hydrologic response, geochemical response and the characteristics are a differently worded and differently ordered list encompassing the parameter lists in (1) and (3).

All these reports for NRC stress the importance of a full scale test facility as part of site characterization. Report (1) in the abstract proposes: "Design verification requires detailed, quantitative response measurements. It is proposed that design verification be conducted in a special test facility." Report (2) assumes that such a facility will be part of the SCR and LA (license application). In the abstract it is stated that: "Tests will be conducted within a in-situ test facility, consisting of an exploratory shaft and an underground test facility at the prospective repository horizon. Plans for these programs are expected to be presented in the initial SCR and the complete results presented in the LA." Report (3) in the executive summary states "...assumes that parameters will be measured initially in test facilities that begin operation during the site characterization phase." It has been assumed that design verification will be assisted with full scale tests. This relaxes somewhat the sampling requirements for the parameters since the model predictions can be observed in the test or experimental stage and relied upon for the stage of actual waste emplacement. Many of the so called indirect, remote, domain, or large volume, measurements that would be valuable in extrapolating point measurements and monitoring changes in parameters with time are not stressed. Consequently, the measurements needed in post closure monitoring are also not stressed.

1.3 Summary of Special Features and Critical Parameters for the 3 Repository Sites

The factors that will control the long term performance of the repository are rock deformations that might rupture the canisters or prevent retrieval, and unexpected changes in the hydrologic regime that might either change the corrosive environment or change the fluid flow in a way to accelerate the transport of radionuclides to the accessible environment.

Post emplacement rock deformation depends on the net effect of excavation, pre-existing stress, and thermal stresses. The fluid state depends on the pre-existing hydrologic regime, the alteration in this regime brought about by the excavation, and by the thermal load. Since the heat generation and movement of isotherms into the rock will continue long after permanent closure, the thermal stresses and concomitant changes in permeability will be constantly changing parameters in the prediction models. These parameters are thus the critical ones for post closure monitoring.

The analysis of rock deformation and groundwater flow can be well predicted if the relevant rock parameters are homogeneous - if the rock mass can be represented by a continuum. Unfortunately none of the sites can be described so simply. Particular characteristics, summarizing from (1), (2), or (3), that pose a difficult challenge to the modelling of each site are:

- (1) Tuff: The rock is highly fractured.
- The rock is unsaturated at the repository level. Fluid content varies from 40 - 97%.
- High porosity.
- Complex lithology (including large openings, lithophases), susceptibility to alteration at high temperature, high clay mineral and zeolite content.
- (2) Basalt: - complex geology - flow structures
- vertical fractures
- aquifers in upper part of flows
- high horizontal stress
- high in-situ temperature
- (3) Salt: - porous and clay-rich interbeds
- plastic behavior especially at high temperature
- induced fluid flow against temperature gradient
- through going fluid-rich zones

For the tuff and basalt sites all the reports identify the fracture content of the rock as the most important property that controls deformation and the hydrologic regime. Report (3) summarizes the importance of fracture characterization very well.

“Repository performance can only be predicted with a low level of confidence if fracture characteristics are not known. Results of in-situ tests designed to investigate the mechanical and hydrological properties of rocks cannot be correctly interpreted without fracture measurements, because fractures will affect these results. Areas of potential instability are unlikely to be adequately monitored because they will be unidentifiable without fracture information. Radionuclides may escape unpredictably through fracture flow paths which have not been detected. New fractures caused by the construction or operation of the repository can cause new flow paths which will change the hydrological response of the rock mass. Unexpected releases of radionuclides may occur and their magnitude, discharge locations, and flow

rates will be unknown if the characteristics of these fractures are unknown.”

“Without adequate information on fracture characteristics, retrievability cannot be guaranteed because failure of the underground workings, including rock burst, could occur unpredictably. Fracture information is required to properly place instruments that will monitor rock behavior. Excessive deformation, occurring along fractures, and induced fracturing, can affect the integrity of waste packages and the waste form.”

Fracture characterization is probably the best example of the difficulty in extrapolating point measurements into global or domain properties. In both the tuff and basalt sites the fractures are near vertical and are obviously not well sampled by infrequent vertical drill holes. Yet it is these vertical paths that would pose the shortest travel path to accessible environments, namely aquifers below and/or above the repository. Fractures also exemplify the problem of scale in many of the critical parameters. It is not known how the properties of a fracture seen in a core sample or televiewer extrapolate to the full scale fracture system. Fractures have a controlling influence in rock strength and it is difficult to obtain rock strength measurements that are representative of the entire repository. Fractures also control the effective thermal conductivity because convective flow can dominate conductive flow and the relative importance of each may change after closure.

An equally pressing problem is the measurement of parameters in the unsaturated tuff. Here porosity, permeability, saturation and the characteristic curves are known to be highly variable within the formations. It is known however that a zone only partially saturated under undisturbed conditions can become saturated under the influence of the heat source and fractures. The fractures would then be fluid filled and would become fast paths to aquifers instead of barriers to fluid flow as they are when unsaturated. The saturation is mentioned as a critical parameter in all three major reports. The situation is stated most succinctly in (3):

“If changes in water saturation are not monitored throughout construction, operation, and decommissioning of the repository, it is impossible to verify

theoretical predictions regarding the ability of the repository to isolate the HLW. Therefore, continual monitoring of water saturation in and around the repository rock is crucial to confirming the adequacy of the repository.”

The same urgency is attached to the characteristic curves and to temperature which control the convective two phase flow.

Finally, fluid flow itself is a parameter of overwhelming importance since it will be this net flow which would transport radionuclides to the accessible environment. It is stated that flow is not directly measurable and that it must be interpreted from other measured parameters such as fluid potential, permeability, etc. However fluid flow is one of many flows possible in a fractured porous medium each of which is driven by a gradient of some sort. Moreover these flows are coupled so that a flow of one type (e.g., fluid) generates gradients in another (e.g., temperature). A strong coupling exists between fluid flow and electric potential gradient and in fact the electric fields generated from fluid flows, and changes in flow, are routinely used to find fluid leakage paths in dams. It seems to be a major oversight in all these reports not to have cited this powerful direct method of measuring fluid flow and particularly changes in fluid flow.

Before discussing in detail the measurement of the parameters needed in monitoring after decommissioning, it is important to note that it is usually a change in a parameter that is needed to tell if the repository performance is behaving as predicted. We will need to know if a preexisting fracture system changes due to changing stress fields, because this would modify the output of the model predicting fluid flow or convective saturating mechanisms. Similarly we would like to know if changes in saturation fall within a range that is predicted and acceptable. For many of the indirect methods advocated in Reports (1), (2) and (3) the ability to detect changes in a parameter is much better than the ability to measure absolute values of the parameter itself.

We now assume that monitoring of performance at the canister and room level has confirmed the behavior expected during the period of retrievability and that, furthermore, the model validation has been successful in some probabilistic sense so that

projections into the future are acceptable.

What can change after decommissioning that might bring about unexpectedly poor performance?

The studies we have reviewed suggest that the following situations will or could arise:

- (1) after closure the repository will return to hydrostatic pressure from atmospheric pressure. This will occur along with resaturation of the rock in the canister area and in the near-field.
- (2) resaturation will obviously affect the thermal regime. The balance between convective and conductive heat flow will be altered, steam pressure may become a factor and the chemical composition of the fluids may be altered by the boiling (and condensation) and water-rock interaction at high temperature.
- (3) The gradual heating of a greater and greater volume will continue to change the stress field within the repository. This will alter the fracture openings and permeability (opening fractures perpendicular to the minimum stress and closing orthogonal sets). This will fundamentally alter the fluid flow through the zone and will in turn modify the heat flow.

All of these phenomena will have been predicted, and the goal of the post closure monitoring is simply to assure that what does happen is within the predicted bounds.

All of the referenced reports indicate that there are few direct methods for measuring critical parameters in the post closure period, and only 'geotechnical instrumentation presently available or easily within the state of the art is considered' (Report 1). It also states that there are parameters that cannot be measured directly but can be interpreted from other measurements. And finally these reports also allude to the fact that future instrumentation may allow repository monitoring using a yet unidentified remote sensing methods.

We have identified critical parameters from the above studies that we believe can be monitored indirectly or directly without penetrating the repository. We have also

identified several new parameters and measurement techniques which, while alluded to in some of the reports have now advanced to the point where they merit consideration for performance assessment as well as post closure monitoring.

We will first discuss the direct measurements that can be used. Some of these are mentioned in the previous reports but some were overlooked or have only recently been accepted as useful tools. Next we will review the indirect methods that are available. Most of these have been used in other fields of study and have also been overlooked in the studies of mined geologic repositories. Finally we concluded with an analysis of some promising areas for development of new monitoring methods.

1.4 Parameters and Monitoring Methods for Post Closure Monitoring

The major parameters of critical interest in post closure monitoring are temperature, stress, displacement, pore pressure, groundwater velocity and permeability (fluid and gas). The following measurements provide direct information on these parameters and the measurements can be made without access to the repository.

(1) Temperature and Gas Monitoring

Temperature can be monitored in shallow (100 m) holes to map the long term development of the isotherms. This could reveal unexpected convection processes in localized zones. Preliminary estimates indicated that the thermally induced perturbations in the form of buoyant liquid and gas flow (convection) will be present. If the formation is fractured and is (water) saturated, the liquid movements will be mainly through the fracture network. Temperature sensors and gas detectors near fractures and fault zones may detect heat and gas flow changes. Durability or ease of replacement of the sensors is a crucial issue to assess fully the impact of long-term evolution of buoyancy distortions. If the repository is above the watertable in a thick unsaturated zone the gaseous flow should also be considered together with liquid flow changes. For fractured porous formations, the capillary forces are likely to hold liquid water in the rock matrix and keep the fractures dry. The fracture network will be the main conduits for the gaseous flow. For

very conductive fracture networks, the gaseous velocities can be very high and the presence of thermally induced gas flow could be detected. Gaseous tracers could be used to enhance the capabilities to detect thermally induced changes in flow conditions.

(2) Ground Surface deformation

The actual ground deformation is one of the most direct measures of the stress state and thermal expansion in the repository. The prediction of this uplift is one of the most basic integral measures of the whole repository system.

(3) Regional and Local Strain

An array of accurate strain meters will monitor changes in the regional stress field. This can be used to continuously update the rock deformation model for the repository and confirm that stresses on the canisters are within normal limits and that actual displacements are within the ranges predicted.

(4) Near Surface Microseismic Monitoring

Seismic sensors buried in relatively shallow holes above the repository (100-meter-deep holes) at spacings of a few hundred meters would detect large acoustic emission (AE) events. AE events will undoubtedly be created as the thermal pulse travels outward from the repository. If the events are confined to microseism-size events (magnitude less than -3) then the size of the source disturbances are probably not significant to cause a break in the integrity of the sealing system. However, detection of activity of greater magnitude from the repository horizon, would probably indicate a problem. In this sense AE/Microseismic monitoring would be useful as a first alert. Resolution on the order of a few tens of meters could be obtained given a dense enough borehole array.

Another class of measurements are referred to as indirect. In this case behavior at the repository must be inferred through the interpretation of measurements of physical properties that may themselves not be related to the critical parameters that are needed. The following are thus indirect methods:

(1) Regional Fluid Potential and Chemistry

At sites where the rock of the repository is saturated, surveys of fluid potentials and analysis of chemical samples in shallow and deep holes around the repository can be used to monitor regional hydrologic regime. Any changes of the characteristics of the hydrologic system should be studied. They can be due to usual hydrologic phenomena, such as change in recharge patterns due to unusual rainfall amounts. They can also be due to buoyancy flow because of the thermal output from the repository. In this case, these measurements will be compared to predicted values from performance assessment of the repository. Any significant discrepancies from the predicted values may point to unexpected behavior of the repository. Changes in groundwater chemistry should also be investigated to see if they can be explained by phenomena not related to any possible abnormal repository performance. Detection of unexpected radionuclide in groundwater certainly requires further measurement and study.

(2) Local Changes in Fluid Flow

Repository performance can also be inferred through changes in water flow in nearby fracture or fault zones, and in a few deep holes away from the repository. In some cases direct pressure and fluid flow measurements can be made. These should be analyzed and compared with predicted repository performance. Changes in fluid flow at the repository and in its close vicinity can possibly be sensed remotely by measuring the electric potential developed by the electroosmotic or streaming potential (SP) process. The effect can be quite large, and surface measurements of the potential distribution have been used to map fluid flow associated with geothermal systems, dam leakage and fluid injection. The SP effects should clearly be monitored during the excavation (dewatering) phase and through the subsequent resaturation period. It should be noted that should a vapor phase be developed during resaturation the streaming potentials of an outward moving vapor phase pressure front would be very large. SP phenomena should be incorporated into the monitoring program during repository desaturation and subsequent phases.

(3) Microgravity

High accuracy measurements of gravity on a dense grid over the repository can, when corrected for the surface uplift, be used to monitor the changing fluid saturation. This technique provides a powerful control or bound for other measurements of fluid content.

(4) Seismic Wave Velocity and Attenuation

This subject is addressed in depth in the section on new developments in repository monitoring and performance assessment. A limited application has already been shown to be effective in monitoring rock properties between boreholes encompassing a heater simulation of a waste canister at the Stripa Mine in Sweden (Paulsson, 1980). This experiment clearly shown a 'hardening' of the rock manifested by an increase in seismic velocity as the rock in the vicinity of the canister heated up. This increase was due to thermal expansion closing up fractures increasing their stiffness and thus increasing the seismic velocity. Similar experiments are being conducted now at the Canadian, Swiss, and Swedish test sites to map fracture zones. Seismic reflection profiling of the repository itself would also show changes in reflectivity and velocity that would show changes in saturation and stress state. The role of seismic methods for indirect rock assessment is mentioned in all the referenced reports but unfortunately in a rather qualitative way that betrays a poor understanding of the power of the method in repository characterization and monitoring. This oversight is continued in the SCP's (since they all seem to religiously follow the lead of the reports 1, 2 and 3.

(5) Electrical Conductivity

This subject is also addressed in greater detail in the next section. The method is particularly promising in monitoring repository performance because the electrical conductivity is governed by the water content and the nature of the water paths through the rock. Electrical current is carried by ions in the water and so the bulk resistivity will depend on the ionic concentration, ionic mobility, as well as the saturation and the degree of connected pores. Conductivity is also temperature and pressure dependent due to the increase in ion mobility with increasing

temperature and the effect of pressure on the apertures of the conduction paths. This very important indirect method is omitted from all the reports except for its inclusion as a foot note to a single 'shopping list' type entry in one table in Report (1).

The SCR's for the three sites mention the application of 'electrical resistivity' but with no clear explanation of its importance or how it is to be measured or interpreted.

1.5 Design of a Post Closure Monitoring Program

We have reviewed certain critical parameters that must be measured in an effective post closure monitoring program and identified some direct and indirect techniques for measuring them.

The next step in implementing a post closure monitoring program is to design actual monitoring schemes for each of the sites. The steps for each site would be as follows:

- (1) Using the site characterization data and the models of repository performance, predict the response, and changes in response, that would be detected by the measuring schemes discussed above. This modelling would concentrate on extreme situations. For example, models of multiphase convective flow in a fracture zone extending to the surface would be used to predict the temperature-time relationship for shallow temperature measurements in such a zone.
- (2) Evaluate the 'normal' variations that might be expected in the various monitoring measurements to establish the levels, above which significant deviations from normal behavior must be detected. This step would involve not only the normal or predicted changes due to the repository but would include normal changes due to seasonal variations or other background variations and fundamental noise levels of the various measuring methods. This step would also involve an assessment of existing or feasible instrumentation and measurement methods.
- (3) Immediately begin base line measurements. These should start before excavation so that there will be a baseline series of measurements against which subsequent

changes will be monitored. The measurements are also critical for step 2 above in which it is necessary to establish the normal variations for the various parameters being monitored.

The design of the post closure monitoring program is not a trivial exercise inasmuch as it will require extensive modelling of the hydrologic regime, the thermal regime, and models of stress distribution and deformation. The measurement methods, however, are not that complicated and require only relatively shallow holes and straight forward instrumentation. Since the methods must be noninvasive by nature, the monitoring will not interfere with scheduled construction and performance confirmation activities; in fact most of the methods we have reviewed will assist materially in the latter task.

Section 2

2.1 Research Recommended for Post Closure Monitoring

In Section 1 we identified certain monitoring methods that have direct application to post closure monitoring and which are currently planned for performance assessment throughout the repository schedule. We also identified some powerful methods that could be used for monitoring post closure performance (e.g., gas measurements and steaming potentials) that are direct measures of critical parameters that were not included in all the performance assessment reports to date. Finally we identified several very powerful parameters which indirectly relate to critical parameters in the repository - the seismic velocity and attenuation, and electrical conductivity of the rocks. These parameters have by and large been omitted from previous studies and yet they relate directly to the following parameters which have been currently identified as critical for repository evaluation:

- fracture content and geometry
- fluid saturation
- change in stress
- temperature

2.2 Seismic Methods

The seismic methods can be divided into the active and passive methods. The passive methods involve "listening" to seismic energy being created by stress changes or natural seismicity such as microearthquakes or acoustic emissions (AE) near the underground openings. These are discussed above. Active methods involve introducing energy into the ground and observing how the seismic waveforms change due to inhomogeneities or anisotropy in the rock. Both the direct and reflected arrivals of seismic waves can be used for this process. Seismic reflection methods are used extensively in the petroleum industry for structural delineation. The utility of seismic techniques will depend upon the resolution obtainable in a given rock type. For this

reason this discussion will be mainly directed towards the seismic methods that have the highest resolution. The goal of seismic surveys is to describe or map the velocity and attenuation of seismic waves through the volume of interest. In general, this process is referred to as imaging although the extent to which a complete or 3 dimensional image can be formed depends on the availability of a suitable distribution of source-receiver combinations and the frequency content of the seismic waves. When a cross section of seismic parameters can be determined the process is also referred to as tomography.

Seismic imaging could play very important roles in site characterization and performance confirmation and monitoring tasks. It can be used to estimate and extrapolate the extent and shape of rock property distributions that are measured only at discrete points in-situ. It can also be used very effectively to detect features (especially fracture systems) not even mapped in the exploratory or excavation phase, and it can be used to monitor changes in properties in the repository area from measurements made entirely outside the critical volume.

Elaborate and extensive plans exist to observe and measure the response of the rock at discrete locations both during in-situ testing and repository construction. Predictions of the response of the rock are based either on empirical models or theoretical, including numerical, models. The latter models, in particular, predict changes in displacements, strains and stresses, as well as fracturing, induced by excavation and heating. It is extremely difficult to measure changes in the rock surrounding excavations, and an extensive and costly program of convergence, extensometer and stress measurements is proposed for each of the sites. The nature of these measurements is such that they can be made only at a limited number of points in the rock mass. The most informative predictive models provide information about these changes throughout the rock mass, but the comparison between experimental observations and predictive calculations, however, must be made on a point by point basis. This is less than satisfactory, because the only extensive information is that provided by the theoretical models. Just as numerical models that show the complete geometry of these changes are greatly more informative and useful than even large tables of point values, so would field

observations providing a continuous geometrical description be vastly more informative than any number of point measurements, let alone the limited numbers that are proposed. Point measurements are, however, still useful to provide precise values for comparison with theoretical prediction and tomographic observation. Most of the current in-situ test plans recognize the potential value of geophysical methods and include some seismic and electrical surveys. However, none of the plans incorporates the full observational power of proper tomography.

The transmission and attenuation of seismic waves through rock depends upon the elastic parameters of the rock which depend upon, among other things, the state of stress and strain, temperature and fluid saturation. As recent research shows, high-frequency seismic wave propagation is also very sensitive to fractures in the rock. Seismic tomography can, therefore, be used to detect changes in the condition of the intact rock mass, to locate major preexisting and new fractures as well as to measure overall changes in the apertures of these fractures. The methods that can be used for these studies use either sources on the surface and detectors in a borehole (referred to as Vertical Seismic Profiling, VSP), or in a cross-hole configurations with both sources and receivers in boreholes.

In a post closure monitoring application it is also important to note the effect that water has on the propagation of seismic waves. As a rock is saturated, or dried, velocity changes of 20 to 30 percent are seen in relatively unconfined samples. An example of this is shown in Figure 1, taken from the work of Mochizuki (1982). A dramatic rise in compressional wave velocity occurs during the very last stages of saturation; there is little dependence on saturation up to about 90%. This is in marked contrast to the effect of saturation on electrical conductivity that we will discuss below. The attenuation of both compressional and shear waves is strongly affected by saturation as shown in Figure 2. These results, reported by Ito et al. (1986) show attenuation, here characterized by the inverse of the quality factor, Q , for dry, partially saturated and fully saturated rock. The attenuation is most pronounced at low confining stress. There is a very different relationship between Q and saturation than between velocity and saturation. This illustrates the need to study attenuation as well

as velocity in any seismic experiment to determine the fluid content in a rock mass. Also, water plays a crucial role in the generation of pore pressure changes which will significantly affect the rate and generation of AE/microseismic events, especially in the presence of thermal loading.

An excellent demonstration of how stress and fluid content can be monitored using seismic methods is illustrated in Figure 3, which shows the result of monitoring the P-, S-wave amplitudes, and acoustic emission activity at the Climax Spent Fuel experiment over a period of several years. At the Climax experiment spent fuel and heaters were used to simulate the heat and radiation at the center of an 8,000 canister array. As seen in Figure 3a, as the rock is heated, and consequently dried out, the S-wave to P-wave amplitudes change dramatically compared to the unheated zones. In Figure 3b it can be seen that the heating of the rock also caused stress release in the form of acoustic emission activity. It is interesting to note that the AE activity was most pronounced during times of heat changes, i.e., during heater turn on or off. Because of this, AE monitoring may be very useful for determining relatively sudden changes in the stress state of the repository.

The success of using seismic wave propagation as a monitoring tool will depend upon the resolution obtainable. One usually thinks of the resolution of the seismic methods in terms of $1/4$ to $1/2$ wavelengths. For frequencies of 100 to 200 hz. this translates to a maximum resolution of 5 to 10 meters. However, recent theoretical and laboratory work shows that a single fracture can significantly affect the propagation of seismic waves with wavelengths much larger than the fracture width. This is due to slippage across the fracture or along the fracture as a seismic wave passes through it. It is not so much the width of the fracture that affects the seismic wave as the "stiffness" or compliance of the fracture. The implication of this fracture stiffness theory is that very thin discontinuities can have significant effect upon the propagation of an elastic wave. Shown in Figure 4 is the attenuation and delay as a function of stiffness on the P-wave as it passes through a single fracture. Usually one thinks of seismic resolution in terms of wavelength compared to the thickness and lateral extent of a bed or other feature. In the stiffness theory the lateral extent is still important, but

the thickness of the features can be much less than the seismic wavelength.

We have confirmed the basic predictions of stiffness theory for wave propagation through fractures with laboratory measurements on individual fractures in rock cores. The stiffness is first derived from static stress-strain measurements under compressive loads across the fracture. These values are then substituted in the theoretical expressions for the transmission coefficient and compared to actual measured transmission coefficients on the same sample. Laboratory measurements and theoretical measurements using the appropriate stiffness, impedance and velocity are shown in Figure 5. Part (a) shows the experimental relationship between the stiffness and the applied stress. Part (b) shows the transfer function as a function of frequency for various applied stresses, and Part (c) shows the theoretical transfer function as a function of frequency for various stiffnesses (which were taken from the first curve for the range of stresses shown in the second curve).

This stiffness theory is also attractive from several other points of view. It has been shown that the ratio of the velocity of a seismic wave perpendicular and parallel to a set of stiffness discontinuities is a function of the spacing of the discontinuities as well as the stiffness. Thus, given the stiffness and the velocity anisotropy, one could determine the average fracture spacing or density. Or, alternatively, given independent information on fracture density, one could determine the fracture stiffness and relate this stiffness to actual fracture properties such as those discriminating between filled and fluid filled or partially saturated fractures. In any case, there is sufficient reason to expect fracture content and fluid saturation to be reflected in the velocity, amplitude, and polarization of the shear and compressional waves. For the purpose of post-closure monitoring the concept of fracture stiffness and its effect upon the propagation of seismic waves is very important. In a monitoring mode one would look for changes in wave propagation characteristics as a function of time rather than absolute values. Depending upon travel paths and rock types a change of just a few percent in the velocity of a 50-meter zone would be detectable. Thus, changes in the fracture and/or water content of the repository horizon and changes due to inflooding or thermal loading (i.e., either drying or resaturation) would be detectable.

Vertical seismic profiling (VSP) techniques have been mainly used for elucidating subsurface structures and determining velocities. In addition to the more conventional uses of VSP, we have been investigating the use of three-component VSP's for fracture detection and characterization (Fig. 6). Fracture detection using both compressional (P) and shear (S) waves depends on the anisotropy introduced by the fractures, which is in turn the result of the effect of compliance or elasticity of the fracture in response to a propagating wave. We have carried out field exercises with this technique and have confirmed the theoretical predictions that fracture systems introduce a significant anisotropy in seismic wave velocities.

In addition to describing structure and fracture content it seems possible to relate the seismic response of the rock mass to the hydrologic response. The idea is to tomographically map the variation in the P and S wave properties and relate the resulting anomalies to the actual fracture density, orientation, and spacing. An example of this approach is shown in Figure 7. Shown are ray paths through a model of fractured rock. This fracture model was actually generated by modifying a code that is used to model the hydrologic response of fractured media. In this way we can compare the seismic response to the hydrologic response. In a conventional approach to ray tracing, the fractures, due to their very small width, would have little or no effect on the ray parameters. In the programs that we have developed we have incorporated the effect of fracture stiffness in addition to the effect of the bulk rock properties. The fractures in Figure 7 have zero thickness but have finite stiffness. The area modeled in Figure 7 is 1 km by 1 km. Figure 8 shows the resulting P-wave waveforms for 40 Hz wavelets. As can be seen the stiffness has a significant effect on the seismic energy.

In summary, field and modeling studies have shown that fractures and changes in fracture system properties have a measurable effect on the propagation of seismic waves. It appears possible to use shear wave anisotropy and 3-D tomography to map the orientation, density, and spacing of fracture sets in the field and to be able to give the hydrologist/reservoir engineer useful information on the fluid flow regime. In a monitoring sense seismic methods hold great promise for detecting water content changes and fracture changes due to thermal loading and/or stress redistributions from

the closure or readjustment of underground openings. The key to the seismic, as well as the other geophysical techniques, is detecting changes from a known baseline. A few percent change in rock properties produces effects that are easily detectable. These seismic methods would be particularly informative if used in conjunction with the electrical methods discussed below. It is important that these methods be implemented early in the design and construction phase so that departures from the natural or undisturbed state can be followed through time. Given the time frame of repository monitoring new instrumentation capable of much better resolution will undoubtedly become available.

2.3 Monitoring with Electrical and Electromagnetic Methods

Electrical methods seem particularly promising in mapping and monitoring the groundwater regime of a repository since the electrical conductivity of rocks depends almost entirely on the fluid saturation, salinity and its distribution. Electrical and electromagnetic (em) methods have traditionally been used to simply detect the presence of good electrical conductors (e.g., sulfide orebodies) or to determine the electrical layering in groundwater or petroleum exploration. Quantitative interpretation in terms of rock properties or even accurate mapping of the subsurface distribution of electrical conductivity (imaging), is not as advanced as that being done seismologically. Only recently have numerical and theoretical studies advanced to the point where quantitative imaging complementary to seismic imaging may be expected.

The electrical conductivity of rocks and unconsolidated sediments in the upper few km of the earth's crust is governed by the water content and the nature of the water paths through the rock. Electrical current is carried by ions in the water and so the bulk resistivity will depend on the ionic concentration, ionic mobility, as well as the saturation and the degree of connected pores. Conductivity is also temperature and pressure dependent due to the increase in ion mobility with increasing temperature and the effect of pressure on the apertures of the conduction paths (Fig. 9).

Most studies on the electrical conductivity of rocks have been on sedimentary rocks because of their importance in petroleum and groundwater exploration. Archie (1942, 1947) established an empirical relationship between the pore fluid resistivity, ρ_p (inverse of conductivity), the porosity ϕ , and the formation resistivity, ρ_f which is now referred to as Archie's Law:

$$\rho_f = a \rho_p \phi^{-m}$$

where a and m are constants for a given rock type. For a very wide range of sedimentary rocks and for some volcanic and intrusive rocks as well, the constant, a , is close to unity and m is close to 2.0.

Fluid saturation has a very dramatic effect on the conductivity of porous rocks. As water is withdrawn from a saturated rock, the large pores empty first but, since the resistivity is mainly controlled by the small water passageways, the bulk resistivity increases slowly: the dependence is roughly proportional to one over saturation squared. As desaturation progresses a critical saturation is reached at which there is no longer any water to conduct along some pores. This breaking of conduction paths leads to a much more rapid increase in resistivity, roughly proportional to one over saturation to the fourth power. The critical saturation depends on the rock type (the nature of the porosity) and may depend strongly on the role of fractures that are present. Combined with seismic velocity and attenuation the electrical measurements would be very valuable for monitoring the progress of resaturation in a repository.

An important and little studied aspect of rock conductivity is the role of fractures on the resultant bulk properties. Laboratory studies concentrate on small intact samples which almost by definition do not include open fractures or joints. Field studies using surface resistivity measuring arrays are usually too strongly influenced by the inhomogeneous nature of the near surface to allow any distinction between fracture and pore porosity of a particular rock unit. With the increased measurement accuracy and resolution provided by subsurface techniques, and the interest in monitoring time changes in resistivity, it is now possible to investigate more closely the role of fracture porosity on the electrical conductivity of large rock masses.

It is well known that the hydraulic conductivity or permeability is strongly influenced by the mean aperture, orientation and spatial distribution of fractures. We have also discovered in the preceding section that seismic velocities are strongly affected by fractures in rock. It remains to develop expressions for the electrical conductivity of such rocks, and to take advantage of this valuable physical property for characterizing and monitoring large subsurface volumes of rock.

The simplest model of a fractured or jointed rock is one in which the fractures are parallel thin layers of conductivity σ_1 in a rock with matrix conductivity σ_2 . This model and the dependence of conductivity on the fracture and bulk porosity is shown in Figure 8. Analysis of this model reveals that a very small fracture porosity can have a dramatic effect on the conductivity of the rock. Fracture or joint porosity is in the range 0 to 2%. In tight or low porosity rocks the fracture porosity may equal the bulk rock porosity. For example if the fracture porosity is 0.005 and the rock matrix porosity is 0.05 the electric conductivity in the direction of the fractures is three times the rock matrix conductivity.

That fractures do play an important role in rock resistivity is practically demonstrated in the work by Brace and Orange (1968a, 1968b). Their work on the effects of confining pressure on the resistivity of a water-saturated granite showed that at low pressures the resistivity increases as the confining pressure increases and they attribute this effect to the closure of fracture porosity (Fig. 10). A resistivity increase of a factor of 10 as the pressure increases could easily be explained by the disappearance of only 0.1% fracture porosity in a granite of 1.0% pore porosity.

The electrical conductivity of the ground can be measured in two ways. In the first, referred to as the dc resistivity method, current is injected into the ground through pairs of electrodes and the resulting voltage drops are measured in the vicinity with other pairs of electrodes. Any or all of the electrodes can be placed in the subsurface, although traditionally surface arrays have been employed. Measurements of voltage and current for different electrode geometries are then used to infer the subsurface distribution of conductivity. These methods are indirect but ideally suited to measure the

properties of a region for which it is impossible to gain direct access. The resulting interpretation of the conductivity distribution is not unique, nor does it provide high resolution of subsurface features. In many applications this latter property is to our advantage since the measurements yield bulk average values of the conductivity which often includes features that are not included in hand samples or borehole logging measurements.

The electrical conductivity can also be measured inductively. Instead of injecting a dc current into the ground, currents can be induced to flow by a changing magnetic field. The source of the changing magnetic field could be a loop of wire carrying alternating current, a long, grounded wire carrying alternating rather than direct current or the earth's natural electromagnetic field. The currents induced in the ground are measured either by detecting the magnetic fields they produce or by measuring the voltage drops in pairs of electrodes. Sources and receivers can be on the surface, below the ground, or a combination of both.

In these inductive or electromagnetic (em) methods the interpretation depends both on transmitter-receiver geometry and frequency used. In principle, the interpretation should be more definitive than with the dc resistivity methods. Rigorous confirmation of this statement in inhomogeneous media awaits the development of generalized inversion techniques for em methods.

The em methods offer some proven advantages over the dc methods. Measurements can be made without contacting the ground; measurements are insensitive to high resistivity zones; depth of investigation can be controlled by the frequency of operation so that large transmitter-receiver spacings are not required; and because of the transmitter source field fall-off, the methods are not sensitive to conductivity inhomogeneities far from the zone of interest. Some recent developments and results for both methods are presented in the following sections.

(a) DC Resistivity Methods

Surface current and potential electrode arrays have been used for many years to determine the subsurface resistivity. The most important recent developments are the use of two and three-dimensional numerical models for interpretation, and resistivity mapping using subsurface electrodes. The latter yields far greater accuracy and resolution than can be obtained with surface arrays. This new development opens the way to more quantitative analysis of ground conductivity and offers exciting opportunities to map and monitor fluid content, temperature and fracture distribution at repository sites. To illustrate the power of subsurface-surface arrays we have picked an idealized model of a repository to show the response from conventional and from borehole to surface arrays.

The model is shown in Figure 11 (Model 1). We have assumed that in excavating and preparing the repository the water content of the rocks has been reduced so that the effective resistivity of a 100-m thick zone has increased by a factor of three over the normal or background value (in this case 200 ohm-m). The results of a standard dipole-dipole surface survey are presented for the model of Figure 11 in Figure 12. The apparent resistivity data are shown as a contoured pseudo section (a standard format) and also projected into a three-dimensional perspective plot. Since we are interested in emphasizing the anomaly caused by the repository, or subsequent changes over time in its vicinity, we have discovered that it is very useful to express the apparent resistivity results as percentage differences from the background. The data in Figure 13 are the percent differences observed in the apparent resistivity relative to the 200 ohm-m half-space. The anomaly is diffuse and broad but quite large enough to be detected. Our experience in high accuracy field surveys has shown that it is possible to make apparent resistivity measurements with an accuracy of 0.1%. For time monitoring with fixed surface electrodes the sensitivity to small changes in the repository resistivity (eg. as water reentered the zone) would therefore be quite high.

Resolution can be improved using subsurface dipole sources and surface receiver dipoles. As shown in the model (Fig. 11), the current electrodes are placed every 150

meters vertically and are treated as a series of dipole sources. The apparent resistivities measured for a given depth of the current dipole and location of surface potential electrodes are plotted vertically midway between the current electrodes and horizontally midway beneath the potential electrodes. The resulting percent differences relative to the background halfspace (Fig. 14) illustrate the greater sensitivity of downhole dipole sources (as compared to arrays confined to the surface) to changes in the resistivity distribution. The anomalies caused by the repository, Figure 14, are almost three times these observed with the surface array, Figure 13.

An equally dramatic definition of the repository boundaries is produced by using percent differences calculated, not in reference to the background halfspace resistivity, but compared to the apparent resistivities observed at a particular depth of the current dipole source. An example is shown in Figure 15 in which all the apparent resistivities in the section are compared to the values observed with the dipole source at 625 meters depth.

Differencing with respect to data at the repository depth reveals that the subsurface arrays reduce near-surface effects that usually confound quantitative interpretation of surface surveys. The results of a surface dipole-dipole survey over the repository model with a small conductive body on the surface is presented in Figure 16. The effect of the surface conductor dominates the response and is observed throughout the section. This makes it very difficult to determine the deeper structure.

In Figure 17 the results for this model are shown for the case of subsurface dipole sources and surface receiver dipoles but with the percent differences calculated relative to the apparent resistivities at the 625-meter level. The effects due to the surface conductors have been almost entirely eliminated. In fact, comparing Figure 17 to Figure 15 in which no surface conductors were present, we see that they are virtually identical. This example illustrates the power of relative percent differencing to remove unwanted near-surface effects: this technique also eliminates 'anomalies' caused by topographic features.

Finally we have chosen a simple example to show the power of these subsurface methods to see changes that might occur after the repository is closed. We have considered a case in which the upper left rectangular quadrant of the repository (dotted outline in Figs. 11 and 16) resaturates, bringing the resistivity of this zone back down to the normal background resistivity of 200 ohm-m. In Figure 18 we have plotted the percent changes that this brings about, referenced against data from the undisturbed repository (Model 1). The pseudo section is diagnostic of the zone that has changed and the changes are well above the accuracy that can be expected for the measurements.

In summary, dc resistivity mapping with combinations of surface and subsurface electrodes appears to have great potential for repository mapping and monitoring. Much work remains to be done in selecting the best array geometries for sensitivity in mapping features of interest in site studies.

One of the most exciting possibilities is to investigate the use of these methods to resolve the fracture-induced anisotropy. The simple illustrations above used two dimensional models with isotropic resistivity. We have three dimensional models in which fracture anisotropy could be introduced, and this, coupled with two dimensional surface arrays of potential electrodes, would undoubtedly greatly improve the resolution of interest in site studies.

(b) Subsurface Electromagnetic Methods

Electromagnetic (em) methods have been used traditionally to locate discrete subsurface conductivity anomalies using surface transmitter-receiver configurations. Our experience in field studies and numerical modelling has been that the resolution of subsurface features is limited by the fact that the frequencies that are low enough to penetrate to the desired depth cannot have a wave-length short enough to define, or image, structural features. The problem is compounded by the surface layers which are invariably conductive, highly variable in thickness and which often act like shields to the subsurface. To overcome these problems, borehole em methods are very

promising. Measurements of magnetic or electric fields are made in a borehole at various depths, and the transmitter may be placed on the surface (surface to borehole), in the same borehole (single hole) or in another borehole (cross hole).

Pulsed borehole radar is an example of an em technique that uses very high frequencies. If the ground conductivity is sufficiently low, megahertz radar waves can penetrate up to 100 m and can respond to dielectric contrasts within the rock mass as well as conductivity anomalies. Radar has been used very successfully in a very low porosity granite repository site study in Sweden in the search for water-filled fractures. The requirement of very low conductivity rock limits radar to a very limited range of potential repository sites. In more conductive rocks the frequency of the em fields must be reduced to achieve significant penetration but then the resolution, or the ability to observe direct reflection images as in seismic methods, decreases as the fields become diffusive in nature. The traditional low-frequency implementation of em methods (less than a few kilo hertz) for ore prospecting relies on quasi-static magnetic induction theory, and basically ignores the wave propagation properties of the fields. In subsurface applications, especially in single hole and cross-hole modes, there are exciting possibilities for em methods in the frequency band between the prospecting and radar frequencies. We will refer to this band as the mid-frequency band.

An example of the results that electromagnetic methods in this mid-frequency band can be used to obtain is shown using a numerical algorithm developed by P. Weidelt (1981) which we have modified for cross-hole and surface-to-borehole applications. The transmitter-receiver configuration and results are shown in Figure 19. A vertical fracture is simulated by a thin 100 x 150 m sheet characterized by a conductivity thickness product of 0.01 Siemens. The host rock resistivity is 10^4 ohm-meters. The vertical field in the receiver hole is presented in nanoTeslas, nT, (or gammas) for a transmitter moment of 1.0 amp m².

The results for the highest frequency used in this example show a pronounced anomaly that could easily be detected with state of the art field detectors and a practical down-hole source with a moment of 100 amp m². We are able to detect even

larger anomalies using a vertical electric dipole and comparable anomalies when a surface loop source is used. The latter is of considerable interest since the source could be moved around (azimuthally and radially) on the surface thus 'illuminating' the fracture from different directions with respect to the receiver borehole. This has geometric parallels with the VSP method.

The fracture model we used in this electromagnetic study would have been undetectable with the DC resistivity methods and yet it is a feature that could be of considerable importance in repository characterization and performance monitoring. What we have modelled is a single fracture of aperture 1.0 cm with a fluid of 1.0 ohm-meter resistivity. This could equally well represent a fracture zone of greater thickness but containing multiple fractures with the same total aperture; in either case the feature is a realistic model for fractures likely to be encountered at these depths.

We have attempted simple tomographic reconstruction, or imaging, of such a fracture using the multiplicity of source-receiver positions that are available, and we have studied the response of multiple fractures as has been done with the seismic methods. Limited forward modelling suggests that these em methods have high sensitivity to position, orientation and conductance of fracture zones but much more work, including field confirmation tests, must be done before these methods are at the same quantitative level as the seismic methods.

2.4 Natural Field Methods

Finally, there have been dramatic developments in natural electromagnetic field methods, particularly magnetotellurics (MT). In MT the impedance of the ground, the ratio of the electric to magnetic field at the surface is measured as a function of frequency. This impedance function is then interpreted in terms of a model of the earth.

MT has been plagued traditionally with problems in data quality and interpretation when the simple layered models used are inadequate. Recently the data quality problem has been solved using the remote reference method developed by Goubau, et al. (1978) and improved in instrumentation (sensors and high dynamic range

acquisition systems now permit high accuracy surveys that were previously not possible). We have field evidence that shows data errors of less than 1% in some frequency bands (Nichols et al., 1985). Interpretation has been a problem because the impedance has simply not been sampled at adequate intervals on the surface. The electric fields change rapidly in response to near surface resistivity variations and bias the impedances which, in effect, masks the deep structure that is sought. This can be treated either by very dense station sampling or by the use of larger lines for the electric field measurements or, preferably, both. In principle the electric fields could be measured over a grid on the surface, with magnetic fields measured at the grid nodes, and the conductivity distribution recovered accurately and unambiguously. Equipment is now available for such surveys but they have not yet been tried.

For repository monitoring this approach seems ideal since the method would be particularly appropriate for measuring changes in the section. It is also very effective for separating shallow changes from those at depth.

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Figure 1. Seismic wave velocity vs. saturation in Massillon sandstone. From Mochizuki, 1982.

Figure 2. Attenuation, expressed as $1/Q$, for compressional (Q_p) and shear (Q_s) waves for dry, partially saturated and fully saturated rock. From Ito et al., 1986.

Figure 3a. Amplitudes of seismic waves as a function of time through the heated (AE5 and AE3) and unheated (AE14 and AE19) rock at the Climax Spent Fuel Test Facility at the Nevada Test Site.

Figure 3b. Acoustic emission activity (events/week) and temperature as a function of time at the Spent Fuel Test Facility.

(a)

(b)

Figure 4a. The change in shape and delay time (ΔT) of a seismic wavelet, $S(t)$, passing through a fracture of varying stiffness, K .

Figure 4b. The spectrum of the transmitted wavelet for varying stiffness, k .

Figure 5. (a) Laboratory measurements of fracture stiffness as a function of normal stress for three rock samples (E30, E32, and E35) (b) Laboratory measurements of the transfer function as a function of frequency for sample E30 for various normal stresses. (c) Theoretical transfer function as a function of frequency for a range of stiffnesses representative of those measured on sample E30 for normal stresses of 1.5 to 70 MPa. Stiffness ranges from $k = 1.6E+12$ to $k = 1.9E+13$.

FRACTURE ZONE MAPPING WITH VSP
THE GEYSERS GEOTHERMAL FIELD

Figure 6. Vertical seismic profiling (VSP) using a surface shear wave vibrator and a three component borehole geophone.

Figure 7. Raypaths through a fractured rock from a source, S, in one borehole to receivers in a second. The fractures were generated using a fracture mesh generating code used in hydrological flow studies. The fractures were assigned stiffness values scaled from the laboratory measurements.

Figure 8. Synthetic seismogram for the raypaths shown in Figure 6 and 40 Hz wavelets. Notice the greater attenuation and travel time delay through the fractured regions.

Figure 9. The dependence of longitudinal conductivity on plane parallel fracture porosity.

Figure 10. The effect of fracture closure on the resistivity of granite. From Brace and Orange, 1968.

2-D NUCLEAR WASTE STORAGE MODELLING: MODEL NO. 1
600 OHM-M REPOSITORY IN 200 OHM-M HALFSpace

Figure 11. Idealized model (Model 1) of radioactive waste repository site. The symbols represent the location of current electrodes in the subsurface dipole configuration.

2-D APPARENT RESISTIVITY DATA: MODEL NO. 1
SURFACE DIPOLE-DIPOLE SURVEY WITH $A = 200$ M
CONTOUR INTERVAL: 3.00 OHM-METER

Figure 12. The dipole-dipole apparent resistivity pseudo section for Model 1 and a three dimensional perspective view of the contoured apparent resistivities.

2-D PERCENT DIFFERENCE DATA: MODEL NO. 1
 SURFACE DIPOLE-DIPOLE SURVEY: A = 200 M, REF: HALFSPACE
 CONTOUR INTERVAL: 1.0 PERCENT DIFFERENCE
 DIPOLE SEPARATION

Figure 13. The pseudo section, and perspective view, of the difference between the apparent resistivities for the model and the background resistivity, 200 ohm-m, expressed as a percent of background (the percent difference referenced to the half space).

2-D PERCENT DIFFERENCE DATA: MODEL NO. 1
 DOWNHOLE DIPOLE SOURCE: A = 150 M. REF: HALFSpace
 CONTOUR INTERVAL: 1.00 PERCENT DIFFERENCE
 DISTANCE FROM SOURCE WELL (METERS)

Figure 14. The pseudo section, and perspective view, of the percent differences for the borehole dipole sources referenced to the half space.

Figure 15. The pseudo section, and a perspective view of the percent differences for the borehole dipole sources referenced to the apparent resistivities obtained with the source dipole at 625 m depth.

2-D NUCLEAR WASTE STORAGE MODELLING:
50 OHM-M SURFACE CONDUCTOR OVER 600 OHM-M REPOSITORY

Figure 16. The repository model with a shallow, 50 ohm-m, conductive body (Model 2) and the resulting perspective view of the contoured dipole-dipole pseudo section.

2-D PERCENT DIFFERENCE DATA:
DOWNHOLE DIPOLE SOURCE: A = 150 M; REF: 625 M DEPTH
CONTOUR INTERVAL: 1.00

2-D PERCENT DIFFERENCE DATA:
DOWNHOLE DIPOLE SOURCE: A = 150 M; REF: MODEL 1
CONTOUR INTERVAL: 0.50

Figure 18. The pseudo section and perspective view, of the percent differences for Model 1, with borehole sources, when the upper left quadrant (dotted) of the repository has returned to 200 ohm-m. Apparent resistivities referenced to the undisturbed, 600 ohm-m, repository.

Figure 19. A profile of the imaginary, or quadrature, component of the vertical magnetic field in one borehole from a vertical magnetic dipole source at a fixed depth in another. A vertical fracture lies between the holes.