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ABSTRACT

The present paper presents considerations on studies that would be required for preclosure monitoring and performance confirmation of a nuclear waste geologic repository in an unsaturated zone. The critical parameters that should be monitored are reviewed and two scales of measurement relevant to monitoring activities, room scale and repository scale, are taken as a framework for investigation. A number of monitoring methods based on geophysics, geohydrology, and geochemistry are briefly summarized for their potential usefulness for preclosure monitoring and performance confirmation of the geologic repository. Particular emphasis is given to measurement of the spatial distribution of parameters in contrast to single-point measurements of quantities.

I. Introduction

A program of performance confirmation based on preclosure monitoring can be designed to verify whether or not a nuclear waste geologic repository is functioning within the limits of predictions from performance assessment studies, limits that satisfy established criteria for the containment of radioactive waste.

The process prescribed by the Nuclear Waste Policy Act and the pertinent regulations embodies a compelling logic that recognizes the uncertainty inherent in any major geotechnical enterprise. At each stage, the decision to proceed is contingent upon satisfactory information obtained in a preceding stage. This logic makes it essential to maintain the option to retrieve the waste up to the very last stage of repository development and waste emplacement. Indeed, experience with large geotechnical or mining enterprises has shown that it is necessary to anticipate that unexpected conditions may be revealed at any stage of the entire enterprise. Figure 1 illustrates the interplay between the information available and the investment in repository development at every stage, from inception through waste retrieval or repository closure, as the case may be. The magnitude of the investment in the repository increases at each stage as the uncertainties about the geologic environment and repository performance diminish with increasingly comprehensive knowledge about the site. The most expensive decision, whether to retrieve the waste or close the repository, is reserved for the end.

The purpose of this document is to highlight the importance of collecting and analyzing information throughout the period of repository construction and waste emplacement. Data collection and analysis can be accomplished through a program of preclosure monitoring. The magnitude of the decision of whether to retrieve the waste or not must be based on unassailable evidence about the properties of the geological environment and the performance of the repository. In this context, preclosure monitoring assumes major significance in the logic leading to an informed and defensible decision that will have to be taken concerning retrieval, after an enormous investment in the repository has been made.

Initially, based on a concept of the behavior and properties of the subsurface system developed through surface-based exploration, a potential repository design is developed. At Yucca Mountain, the potential performance of the proposed repository based on this initial concept of the subsurface system appears to be satisfactory, thereby justifying a considerable increase in the investment so as to develop the Exploratory Shaft Facility (ESF). The ESF allows the surface-based concept of the geological system to be checked by direct observation and enables measurements and experiments to be made to determine the behavior and properties of the rock mass pertinent to repository construction and waste isolation. Such experiments and observations could not be done from the surface. Undoubtedly, the additional information about the rock mass revealed by the ESF activities will confirm some aspects of the original surface-based concepts and modify others. This leads to a more comprehensive and less uncertain concept of the subsurface geologic system and a modified concept of the proposed repository. If the performance of this modified repository concept is still satisfactory, the investment in the repository proceeds to the next, more costly, stage of repository construction and waste emplacement.

It is important to recognize that the ESF enables the behavior and properties of a very small sample area of the rock mass to be observed and measured. Excavation and construction allow this concept of the subsurface system (applicable to the ESF area) to be tested against observations and measurements extending throughout the repository area. It is quite likely, indeed probable, that significant differences will emerge between the behavior and properties of the rock mass in the ESF area and elsewhere in the whole repository area. (It would be equally important to demonstrate that no significant differences between ESF and the whole repository exist, if this was the case.) These differences may require further modifications of the repository concept to be made in order to achieve satisfactory performance. The construction and emplacement stage provides further, essential information not only in areal extent, but also in time. A favorable decision to proceed from ESF testing to construction is likely to be made on the basis of observations and measurements over a few years. Observations and measurements during construction and emplacement can be made over a period for 50 years.

Just as the ESF observations and measurements are needed to provide the information on which to base the decision to invest in the costly stage of repository construction and waste emplacement, so is a program of preclosure monitoring and data analysis during construction and emplacement needed on which to base the even more costly decision of whether to retrieve the waste or close the repository.

In this paper, system responses critical to performance confirmation that may be determined from preclosure monitoring are defined at both the room and repository scales, and the applicability of geophysical, geohydrological, and geochemical methods for monitoring these responses is examined. Particular emphasis is given to measurement of the spatial distributions of parameters in contrast to single-point measurements of quantities. These spatial distributions may comprise a large number of point measurements that can be mapped or imaged through the volume as a whole or of measurements of parameters such as seismic velocity or electrical potential which may be measured at specific points but whose values reflect the integrated effect of the volume through which the signal has passed.

Measurement of parameter distributions has received little attention, but it has the potential for revealing overall information concerning a volume that scattered single-point measurements, which are often strongly affected by local heterogeneities, cannot provide alone. In general, both single-point and distributed measurements are needed, and combining them provides a much improved total picture for (a) validation of performance assessment models (especially conceptual models) and (b) validation of techniques for postclosure monitoring.

This paper is a summary of the results of a series of multidisciplinary discussions among LBL geohydrologists, geologists, geochemists, and geophysicists. They are Chalon Carnahan, Neville Cook, Steve Flexser, Iraj Javandel, John Kemeny, Ki Ha Lee, Marcelo Lippmann, Tom McEvilly, Ernest Majer, Frank Morrison, Larry Myer, Chin-Fu Tsang, and Harold

Wollenberg.

The next section presents background discussions of possible repository responses to imposed stresses and proposed monitoring methods, and is followed by an examination of the usefulness of some methods for preclosure monitoring and performance confirmation.

II. Background

Parameters to be Monitored

St. John et al. (1982) have identified several conditions and responses that should be monitored at the canister scale, room scale, and repository scale during various periods starting from the site characterization stage through post-decommissioning. In this paper we have selected a list of "items" that practically copy the ones provided by St. John et al. (1982), and in addition our items tend to emphasize the unsaturated nature of the formation at Yucca Mountain and the importance of major flow paths. Thus our list of critical parameters, as shown in Table 1, includes radionuclide concentration, liquid/gas saturation, liquid/gas flux or velocity, liquid/gas composition, corrosion, temperature, displacement, and major paths (structure). It is important to note that changes in key parameters rather than their absolute values provide information on whether a repository is behaving as predicted. Indeed, for many of the indirect methods of measurement available for monitoring, the ability to detect changes in parameters is much better than the ability to measure absolute values of the parameters themselves. In order to relate measured changes to parameter limits established by performance criteria, it is necessary to have measured baseline values. Baseline values of the parameters and of their possible natural changes will need to be established in the near future, before their disturbance by repository excavation. Anomalous changes exceeding established limits would signal possible detrimental deviations from required performance criteria. Concurrently, continuous monitoring in the preclosure time frame would provide a data base useful for improving predictions of repository behavior in response to "normal" (within established limits) system perturbations.

The state of the hydrologic regime within and around the repository will be of paramount concern with respect to its performance. Without the presence of mobile water (and gases) to serve as a medium of transport, there would be little concern about the long-term isolation provided by a suitably engineered repository. One should be reminded that even in the vadose zones of the Yucca Mountain tuffs the pore space may be as much as 70 percent occupied by water, and uncertain amounts of water can exist in fractures or in perched layers. It has been established that fluid flow in low-porosity rock is largely controlled by fracture permeability and that certain geophysical properties of rock and geochemical properties of rock and fluid are influenced significantly by the fracture system and its state of liquid saturation.

The ability to monitor changes of hydrologic parameters is particularly important in the unsaturated tuffs. Here, porosity, permeability, saturation and (negative) pressure are known to be highly variable within the formations, as well as highly sensitive to changes in stress, temperature, and saturation fields that interact among each other. In general, small changes in one or more of these fields are likely to be reflected by relatively larger changes in the geometry and saturation of the fractures. Thus, as stress states change, open fractures close rather easily in one direction and open in another. A nearly saturated rock will hold all the water in the matrix and manifest a rather small effective permeability; a small amount of additional water could fill the fractures and increase the effective permeability dramatically. A recent study (Binnall et al., 1987) has stated,

> "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."

That fractures can act to amplify small system changes is fortuitous because we have identified several geophysical, geohydrological, and geochemical methods which are sensitive to the characteristics of the fracture network and hence will provide excellent means for monitoring changes. The capabilities provided by these methods are particularly important in regard to the problem of fracture characterization. Extrapolation of point measurements of fracture characteristics to global or domain representations is especially difficult under the conditions extant at Yucca Mountain, where fractures are nearly vertical and are difficult to sample by infrequent vertical drill holes. Yet, it is these vertical fractures that might provide the shortest paths for the potential migration of waste materials to the accessible environment.

Physical and Chemical Processes to be Monitored

Fluid flow itself is a parameter of overwhelming importance because the fluid would be the means by which radionuclides could be transported to the accessible environment. Fluid flow is not directly measurable by remote methods and must be interpreted from other measurable parameters such as hydraulic potential and permeability. However, fluid flow is only one of several flows possible in a fractured porous medium. Others are flows of heat, individual solutes, and electricity (electric streaming potential), driven by gradients of temperature, hydraulic potential, chemical potential, and electrical potential, respectively. These flows are also coupled, so that a given potential gradient can drive a seemingly unrelated flow (e.g., in thermal osmosis a gradient of temperature drives a flow of fluid), or a flow can induce a gradient of a seemingly unrelated potential (e.g., a flow of fluid can induce an electric streaming potential).

The heat released by the radioactive wastes will be stored largely in the subsurface rock for thousands of years and will distort the hydrological conditions between the repository and the accessible environment. The most obvious natural analogs of thermally induced perturbations are occurrences of geysers, hot springs above a magma body, and geothermal anomalies (Wollenberg and Flexser, 1986). Although we do not expect buried radioactive wastes to generate such strong thermohydrological perturbations, their effects will depend on the ambient conditions of the host rock. Recent studies clearly indicate that thermally-induced perturbations cannot be ignored in the design of repositories (Tsang, 1987; Wang et al., 1988).

Performance confirmation measurements are especially important soon after repository construction and waste emplacement, when the major (and well-defined) changes in stress, fluid pressures, and temperatures are expected due to excavation and subsequent heating. Therefore, it is very important for repository confirmation to measure and evaluate the changes brought about by these activities and to have background data to be able to quantify the changes: any measurements must commence early enough before excavation so that the needed baseline information becomes available.

Two Scales of Measurement

These considerations lead to the identification of two spatial scales for scenarios of repository change and for corresponding monitoring activities. The *room scale*, on the order of a few tens of meters, would be applicable to preclosure period monitoring and would provide detailed information on material properties and local response of the repository to imposed mechanical, hydraulic, and thermal stresses. These data would be invaluable for calibrating and improving numerical models of system performance. On the other hand, the *repository scale* would be the appropriate scale for responses affecting the repository as a whole, such as large-scale perturbation of the hydrologic flow field. Numerical models and monitoring methods used at the repository scale may depend on data acquired at the room-scale and in this sense studies conducted at both scales are interrelated.

III. Potentially Useful Methods to Monitor Critical Parameters

Comparisons of parameter requirements for performance confirmation and site characterization reveal two important differences. First, for site characterization, absolute values of the parameters are needed, whereas for performance confirmation, it is the changes in parameters in response to thermal, mechanical, and hydrologic perturbations that are most important. For example, the absolute value of porosity may be measured for site characterization, but changes in porosity measured during preclosure monitoring may be more useful for performance confirmation. Second, the objective of site characterization is to provide data from which predictions of repository behavior can be made, but the objective of performance confirmation is to evaluate the accuracy of these predictions. The baseline data, parameters, and monitoring methods needed to achieve the performance confirmation objective are not necessarily equivalent to those for site characterization. For example, permeability is a primary concern for site characterization, whereas fluid flux is important for performance confirmation.

A number of geophysical, geohydrological, and geochemical methods are available for monitoring system responses. This section provides descriptions of the methods that could be used to evaluate the critical parameters. Table 1 summarizes the methods with respect to the critical parameters. For each method, the way in which the parameter is measured or inferred is briefly reviewed below. In the subheadings for each method, the methods appear in regular type and the *critical parameters* that are being measured or inferred appear in *italics*.

Seismic Velocity and Attenuation Measurements

Seismic velocity is primarily determined by the elastic properties and density of the rock mass, and therefore will yield information about parameters and processes which cause changes in these properties in time or space. Seismic attenuation is primarily due to inelastic processes which lead to energy loss.

Seismic Velocity and Attenuation ↔ *Major Paths (Structure)*

Rock mass structure, such as layering, faults and fractures, which produce seismic impedance contrasts, can be imaged using both velocity and attenuation data. In the case of Yucca Mountain, the methods with the most promise for preclosure monitoring and performance confirmation are surface to borehole and crosshole imaging, and high resolution reflection profiling. The features of interest at Yucca Mountain are probably the fractures and faults along which the water can migrate. It is crucial to know the density, orientation, aperture, and spacing of these features in order to predict the transport behavior of the ground water system.

A very comprehensive and extensive technology has been developed through petroleum exploration for imaging large scale structures. There have been numerous studies showing that seismic waves are sensitive to rock type and fracture content. Recent studies have also shown that fractures cause significant anisotropy that can be mapped by using three-component seismic sources and receivers. In a monitoring mode, changes in seismic velocity of a few tenths of a percent can be measured so that changes in stresses across, or saturation of, major features such as fracture zones can be detected.

Seismic Velocity and Attenuation ↔ *Displacement*

Displacements in the rock mass will occur in response to excavation of the underground openings. These displacements will change the elastic modulii and hence change the seismic velocities in the rock mass. Rock displacement from fracturing will cause increased attenuation and reduced seismic wave velocity. Seismic surveys conducted on a room scale would be expected to detect the effects of these displacements.

Seismic Velocity and Attenuation ↔ *Temperature*

Temperature also affects the elastic constants of the rock. The general effect on unconfined samples is to lower the seismic velocity and raise the attenuation. At pressures representative of Yucca mountain the effect would be expected to be about a 20 percent change from 20 to 200°C (Mobarek, 1971). However, on a rock mass scale, thermal effects may be more complicated. Studies in confined rock indicate that as the temperature increases the microcracks close and the velocity actually increases as does the amplitude of the seismic wave (Paulsson, 1983). At higher temperatures, i.e. above 300°C, the rock will fracture and cause the velocity and amplitude of the seismic waves to decrease, (Gregory, 1976). Such high temperatures are not anticipated in the repository except, perhaps, in the very near field.

Therefore, if thermally-induced displacements tend to increase void space, or "loosen" the rock mass, the velocities would be expected to decrease and attenuation to increase. The opposite effects would occur if void space decreases and the rock mass "tightens." Such effects have been observed when temperature increases around an excavation resulting in closure of fractures. Imaging of seismic velocity and attenuation both on the room scale and the repository scale would provide information about changes in rock temperature with time.

Seismic Velocity and Attenuation ↔ *Saturation*

Theoretical, laboratory, and field studies have demonstrated that both the attenuation factor and the velocity of seismic waves are affected by the degree of water saturation (Gregory, 1977), but in different ways. There is a significant difference in seismic velocities between dry and saturated rock. However, since the elastic properties of rock are not affected greatly by liquid until the rock is almost completely saturated, velocities change little at low saturation levels and change rapidly as saturation approaches 100 percent.

Attenuation, on the other hand, is more sensitive to introduction of small amounts of water in an initially dry system. Compressional-wave attenuation can be affected by as much as an order of magnitude when the saturation changes from 70 percent to full saturation. Although the effect on the velocity is less (20 to 30 percent), velocity measurements are more stable and easier to make.

The advantage of using seismic measurements is that by using both the shear wave and compressional wave data one can separate the effects of structure and fracture content from effects of saturation, although in monitoring this may not be necessary. Because the S-wave is relatively unaffected by the fluid content of the rock and greatly affected by the fracture content compared to the P-wave, one can separate the effect of crack density from that of saturation.

Acoustic Emission Monitoring

Acoustic Emission (AE) is another geophysical method that shows promise for preclosure monitoring and performance confirmation. AE is a passive measurement that detects the release of seismic energy.

Acoustic Emission ↔ *Major Paths (Structure)*

AE may prove to be a very useful and powerful technique for defining structural characteristics for several reasons. AE activity is a good indication of stress release, thus it is often associated with rock types that withstand stress buildup, i.e. competent rock. In studies of the Climax Stock, it was observed that AE activity was associated with the competent less permeable rock, and was lacking in the "loose" permeable rock. Thus, the spatial distribution of AE activity may indicate the areas of permeable versus impermeable rock. A second use may be to utilize the seismic signals generated from the AE sources as small seismic wave generators for imaging the rock between the AE source and the AE sensor. Thus, given a broad enough volumetric distribution of the AE activity, a three-dimensional image of the structure may be obtainable.

Acoustic Emission ↔ *Temperature*

AE studies (Paulsson, 1983; Majer and McEvilly, 1985) have shown that at temperatures as low as 80°C there is detectable AE activity associated with a temperature increase. The AE in these studies probably was caused by slip along preexisting fractures, in response to an increase in local stress as the rock expanded. Thus, the AE method is a very good indicator of stress buildup due to thermal loading.

Acoustic Emission ↔ *Displacement*

In the above-mentioned studies, the displacement inferred from the AE activity was small in each event, but cumulatively was on the order of several centimeters over a few years time. Thus the AE method is a direct indicator of displacement.

Electrical Potential Measurements

Electrical potential differences arising from processes occurring within a rock mass are measured at arrays of two or more electrodes. The electrodes may be located at the ground surface, in which case they sample distributions of potentials on a scale comparable to that of the repository. Electrodes located within the repository itself can be used to sample electrical potentials arising from processes at scales comparable to that of the room.

Hydraulic and thermal gradients can contribute to the presence of electrical potentials in nuclear waste repositories. Electric power lines could generate electric fields that could interfere with measurement of electrical potentials arising from these gradients. Discrimination of spurious signals is probably more feasible at the room scale than at the repository scale.

Measured electrical potentials can be expected to vary slowly in time as the stress environment of the repository evolves. Anomalous changes of potential could signal the onset of changes in hydraulic gradients, thermal gradients, or electrical properties within the repository.

Electrical Potential ↔ *Liquid/Gas Flux/Velocity*

Streaming potentials are generated by hydraulic potential gradients in the presence of variations of electrical properties. Streaming potentials are often associated with fluid flow fields and have been used as indicators of flow fields. However, it should be emphasized that the driving force for the streaming potential is the hydraulic potential gradient and not the resulting fluid flow also driven by the hydraulic gradient. This implies that streaming potentials could be observed in regions of very low fluid permeability in the presence of heterogeneities in electrical properties within the rock mass being studied. These properties include the coupling coefficient between the electrical and hydraulic potentials and the electrical conductivity of the fluid. Thus, the occurrence of an electrical potential anomaly or sudden changes in an existing anomaly could indicate changes of hydraulic potential accompanied by changes of electrical properties in either or both fluid and solid phases. An example of a process that could induce changes of streaming potential is the onset of fluid flow in fractures subsequent to an intense recharge event.

Electrical Potential ↔ *Temperature*

Thermo-electrical potentials are generated by temperature gradients and are indicative of the presence of heat transport within the volume being examined. The coupling coefficient between the thermal and electrical gradients depends on the composition of the fluid phase, electrical properties of local fluid-solid interfaces, and thermal properties of the fluid and solid phases. Observations over local regions of the subsurface domain could provide at least qualitative mapping of variations of thermal gradients.

Electrical Potential ↔ *Major Paths*

Major paths for fluid flow would constitute conductive shunts for flow of electrical current and would exhibit anomalously low electrical potential drops. Such anomalies should be observable by electrical potential monitoring networks on the repository scale. The potential measurements should be interpreted in conjunction with measurements of electrical conductivity.

Electrical Conductivity Measurements

Electrical methods seem particularly promising for monitoring the groundwater regime since the electrical conductivity for a given rock type depends almost entirely on the pore water content. The bulk resistivity of a rock depends on the porosity (including fracture porosity), saturation, dissolved solids in the pore water, and temperature. Electrical methods can be used to detect zones of varying water content and, most importantly for this study, to monitor temporal changes in the electrical properties of rocks associated with changing saturation, temperature, porosity, and pore water chemistry.

It has been demonstrated (Asch and Morrison, 1989) that resolutions of temporal changes in the electrical properties can be greatly enhanced by using simultaneous surface and subsurface electrode arrays. This is true for both direct current (DC) and electromagnetic (EM) methods of measuring electric conductivity.

Electrical Conductivity ↔ *Temperature* and *Liquid Salinity*

An empirical relationship between the pore fluid electrical resistivity (inverse of conductivity), porosity, and the formation resistivity was established and is now referred to as Archie's Law. For a wide range of sedimentary rocks and for some volcanic and intrusive rocks as well, the formation resistivity is known to be proportional to the pore fluid resistivity and inversely proportional, in most of the cases, to the square of the porosity. The pore fluid resistivity is extremely sensitive to the fluid salinity, and is also known to be temperature-dependent due to the increase in ion mobility with temperature. It is through changes in pore fluid resistivity that predicted changes in critical parameters such as fluid salinity and temperature can be indirectly inferred.

Electrical Conductivity ↔ *Liquid/Gas Saturation*

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 the bulk resistivity increases slowly since it is mainly controlled by the small water passageways. At this point the rock resistivity is roughly inversely proportional to the 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 the conduction paths leads to a much more rapid increase in resistivity, roughly inversely proportional to the 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 the fractures that may be present. Combined with seismic velocity and attenuation, the electrical measurements would be very valuable for monitoring changes of saturation in a repository.

Electrical Conductivity ↔ *Major Paths (Structure)*

Electrical and electromagnetic (EM) methods have traditionally been used to simply detect the presence of good electrical conductors or to determine electrical layering for groundwater or petroleum exploration. Quantitative interpretation in terms of locating conductivity discontinuities, identifying different rock units, and characterizing fracture zones is beginning to be realizable using subsurface transmitter-receiver configurations. A recent study (Zhou and Morrison, 1988) shows that it is now possible to map saturated conductive fracture zones representing major paths for ground water. It is well known that permeability is strongly influenced by the nature of these fracture zones. A diffusion tomography algorithm suitable for low frequency EM fields has been developed for this purpose, and successfully applied to map permeability distributions between boreholes using computer-generated synthetic data. A crosshole configuration, one hole for transmitters and one for receivers, is required for this purpose; the fracture zones do not have to be intersected by the boreholes. The location of, and changes in, major structures conducting fluids can be monitored using EM tomography.

Displacement Measurements

Rock mass displacements will occur in response to creation of the underground openings and the imposed thermal load (and pore pressure changes).

Displacement ↔ *Displacement*

Displacements around an underground excavation are typically measured using extensometers, (which include a wide variety of tools of different designs), inclinometers (or tiltmeters) and surveying methods.

If sufficient numbers of these point measurements were available, it would be possible to construct contours of displacement around each excavation and an integrated displacement profile could be obtained. Ground surface profiles, because of the distance from the excavation, would represent more of an integrated effect of the displacements around many individual openings. Ground surface displacements could be monitored by periodic precise horizontal and vertical-control surveys of a network of monuments.

Displacement ↔ *Major Paths (Structure)*

Displacement magnitudes can be greatly affected by geologic structures. Excavation of subsurface openings results in rock mass deformation toward the opening. Instruments are available which are capable of resolving such deformation in the micron range. Typical measurements are greatly influenced, and may be dominated, by structures very local (~1 m or less) to the measurement location. Because of the small volume of rock mass sampled by typical techniques it is difficult to obtain a displacement distribution over large areas. Therefore, densely spaced measurements of displacement would be needed to identify the effect and location of structures.

At the surface, subsidence may occur as a result of underground mining. The amount of subsidence depends on the amount of subsurface deformation (and volume of material excavated), depth of the excavation, and rock mass structure. If only elastic deformation occurs around the repository excavations, it is doubtful that measurable surface deformation would occur. The spatial distribution of surface displacements could also be affected by the location of faults or shear zones.

Fluid Pressure Measurements

Fluid pressure distribution and its variation with time, in both the liquid and gas phase, is one of the most important parameters needed to monitor fluid flux in the repository block.

Pressure ↔ *Liquid/Gas Flux/Velocity* and *Major Paths (Structure)*

In order to confirm predictions during the repository construction and operation periods, pressure in both the liquid and gas phase should be measured in strategic locations within the repository block. Pressure in the gas phase may be measured by pressure transducers properly housed in boreholes drilled from underground facilities. Liquid pressure in the unsaturated zone may be measured by tensiometers or heat dissipation probes.

The pressure distribution data together with the characteristic curves of the materials in which the pressures are measured, would enable calculation of the liquid/gas saturation and estimation of the liquid flux into the repository. Monitoring air pressure variation across major rock mass discontinuities could give useful information about the permeability contrast between the potential flow conduits and surrounding rock matrix.

Temperature Measurements

The temperature distribution and its variation over time is one of the most important parameters to monitor in the repository because it affects so many processes significantly related to solute transport, like the hydrologic flow field, the stress field, and the rate of chemical reactions.

Temperature ↔ *Temperature*

Previous heater experiments at various underground research sites have shown that prediction of conductive temperature distribution in the rock around the waste canisters can be done very reliably. However, the temperature distribution will be affected by fluid convection processes (e.g., heat-pipe phenomena). Differences between the predicted and measured temperature distributions in time and space should be monitored by thermocouples placed in the boreholes around the room. Accurate positioning of the thermocouples in the vicinity of the canisters is important because of the high temperature gradient. Another method for acquiring a large number of temperature readings on the surfaces of excavations is with an infrared scanner.

Temperature ↔ *Liquid/Gas Flux/Velocity* and *Major Paths (Structure)*

Small water seeps emanating from potential groundwater paths, such as fractures intersecting the walls of underground facilities may occur without being readily noticed. Such seeps may be missed because of evaporation due to the forced ventilation of the facilities. These seeps may, however, be monitored by temperature mapping of the walls using infrared heat sensors. The presence of such localized seeps along the walls of the repository could identify major groundwater paths leading to the underground openings. The magnitude of temperature anomaly could be related to that of the liquid flux.

Use of a robotic infrared scanner to record a continuous image of the rock surface temperature in repository excavations at various times should be studied. Such measurements of surface temperature could be carried out soon after the excavations are made and then at regular intervals, thereafter, even after emplacing the waste. The thermal images could be stored digitally, and comparisons between images taken at different times can be compared with one another and with theoretical predictions using an appropriate numerical code. Visual displays also would be extremely informative. Furthermore, these data would have other benefits such as the confirmation of ventilation design for cool-down in the event that retrieval becomes necessary.

Psychrometry

Heat and mass transport into and out of the repository excavations is central to an assessment of repository performance. Two sets of observations should be employed to determine the spatial and temporal distributions of water, air and heat flow throughout the repository excavation and ending with repository closure. The first set of observations would comprise detailed psychrometry, that is, measurements of air flow, air temperatures and humidities. The second set of observations would comprise measurements of the surface temperatures of the rock walls of the repository excavations using a robotic infrared scanner, as described above under "Temperature ↔ *Liquid/Gas Flux/Velocity* and *Major Paths (Structure)*".

Psychrometry ↔ *Liquid/Gas Saturation* and *Liquid/Gas Flux/Velocity*

Some psychrometric measurements are planned as part of the engineering of the repository ventilation system. Measurements of the wet- and dry-bulb air temperature, air velocities or flow rates, and precise humidity measurements should be made at the air regulators situated at the entrance and exit to each repository panel. In the event that psychrometric measurements are not made at intake and exhaust shafts as well as at main airways for engineering purposes, such measurements should be made at these locations also. Electrolytic humidity meters can measure concentrations of water vapor of parts per million, so that the psychrometric measurements would enable the flow of water and water vapor into the repository to be made with great precision. Changes in the flow of water could be compared with the predictions of models for repository performance to validate their results. Any anomalies in mass transport between panels would provide important warning of major hydraulic features or potentially adverse conditions.

Changes in the heat flow within repository panels can be compared also with the predictions of models for repository performance, to validate their results. Any anomalies in heat transport would provide an important warning of potentially adverse conditions. The value of psychrometric measurements would be enhanced greatly by information that would locate the sources of water inflow. The transport of liquid water or water vapor into or away from the repository excavations can be expected to have a significant effect on rock surface temperatures. For example, the evaporation by the ventilation air of water flowing into the excavations will depress the rock surface temperatures below air-dry bulb temperatures in the vicinity of such inflows. Also, heat pipe effects caused by the evaporation of water near waste containers and its condensation farther into the rock would reduce rock temperatures in the vicinity of heat sources. Such processes could be detected as temperature anomalies by measurements of the rock surface temperatures of the repository excavations, as described above under "Temperature ↔ *Liquid/Gas Flux/Velocity* and *Major Paths (Structure)*".

Psychrometry and Temperature ↔ *Major Paths (Structure)*

In conjunction with data acquired by other studies, the psychrometric and surface temperature data would be invaluable not only for comparison with the predictions of models used for performance assessment but also to identify and locate on excavation surfaces significant hydrologic features and their related structures. They would also provide direct evidence of groundwater flow paths and of unexpected changes in hydrologic conditions.

Liquid/Gas Tracers

The main concern of a nuclear waste repository is radionuclide migration and the travel time to the accessible environment. The most direct measurement is by liquid and gas tracer tests where the tracer velocity (travel time) is measured. Such measurements will give information about parameters that are not normally obtained by other well-established methods, such as effective porosity and dispersivity. Tracers for both of the phases are also very useful as indicators of major flow paths.

Liquid/Gas Tracers ↔ *Liquid/Gas Flux/Velocity*

Two of the key factors in the performance of a repository are the flux and velocity of radionuclides carried by liquid/gas transport. Use of tracer measurements provides a direct measurement of potential travel velocities and other transport parameters. A number of small scale tracer tests at various locations in and around the repository may give a distribution of local parameters controlling such transport.

Liquid/Gas Tracers ↔ *Major Paths (Structure)*

Geologic media tend to show strong heterogeneity. Often major flow paths carry most of the flow through the system. Some of these may not be noticeable geologically, and can only be found hydrologically. Liquid/gas tracer measurements represent the most direct means for detection and measurement of these major flow paths and their associated dispersive-advective parameters.

Liquid/Gas Tracers ↔ *Liquid/Gas Saturation*

While measurements of liquid/gas tracer transport cannot yield directly the saturation values, they are strongly affected by these quantities, through both the relative permeability function and the distribution of water saturation in the system. Thus liquid/gas tracer measurements will be useful in conjunction with other measurements in detecting changes in the saturation distribution.

Collection and Analysis of Liquid/Gas Samples

Collection and analysis of liquid/gas samples during the preclosure time period could be undertaken at both room and repository scales to determine changes in major flow paths and thermohydrological regimes.

Liquid/Gas Samples ↔ *Liquid/Gas Composition* and *Radionuclide Concentration*

Liquid/gas samples would necessarily be point data, but collectively they would provide guidance toward definition of distributions of liquid/gas compositions and their variations in space and time. These samples would provide direct information not only on detailed compositions of liquids and gases, but also on concentrations of any radionuclides. Sampling would be done at identified flow paths. The latter measurements would contribute, over time, to definition of baseline conditions with respect to any radioactive substances in the repository environment.

Liquid/Gas Samples ↔ *Corrosion* and *Major Paths (Structure)*

On the room scale, liquid/gas sample compositions would also serve as monitors of canister failure. For example, detection of anomalous concentrations of hydrogen in the gas samples might provide premonitory indications of impending canister failure by corrosion. In conjunction with other observations, distributions of spatial values of liquid and gas compositions could provide useful information leading to identification of migration pathways.

Radionuclide Concentration Monitoring

The most direct indication of the release of radionuclides within or from the repository will be the measurement of the concentrations of key radionuclides in pore and repository fluids (liquids and gases).

Radionuclide Concentration ↔ *Radionuclide Concentration*

Uranium and members of its decay series, actinide elements, and fission products are components of the waste that can be measured radiometrically. It is assumed that detection systems will be established in critical waste-package handling areas, and in canister-loaded panels to monitor air- and water-borne radionuclide concentrations. Such systems will be configured for remote operation as emplacement of the waste is completed and backfilling progresses.

Radionuclide Concentration ↔ *Liquid/Gas Flux/Velocity* and *Major Paths (Structure)*

It is assumed also that monitors will be located in and around the repository block. Should canisters be breached, extensive radionuclide monitoring at these locations would provide indications of liquid/gas flux and velocity, and major paths of radionuclide release. In this respect, the radionuclides would serve as inadvertent tracers in determining the travel time of the front of the leakage plume to the accessible environment and the composition and concentration of radionuclides within the plume.

IV. Coordinated Multidisciplinary Monitoring

A monitoring program should be carefully coordinated. Such a multidisciplinary effort should be invaluable for the success of monitoring the performance of a repository. The monitoring network for detecting thermohydrological changes in gas, liquid, and tracer flows would be mainly installed in the rock mass around the repository rooms and at the surface. A few deep monitoring boreholes away from the repository could also enhance the detection of changes in space and time induced by the presence of the repository. The room scale measurements could be used to validate the surface measurements during the operation of the repository.

There is the need for research on how to design and establish an appropriate network for geophysical, geohydrological, and geochemical monitoring. Whenever possible, the various monitoring networks should be deployed considering the interrelation between the various parameters being measured, thus optimizing the effectiveness of the monitoring effort.

V. Summary and Further Remarks

To confirm the predicted performance of a nuclear waste repository we need to ensure that both the conceptual model and the predicted processes are correct. Thus, a carefully designed program of preclosure monitoring is needed. The conceptual model of the system includes the geologic and geometric characteristics of the site, such as the lithology/stratigraphy (with appropriate properties for each unit), faults and fracture systems, and heterogeneities. The model should include the physical and chemical processes that occur in the system. All these characteristics are site specific. Hence, predictions of repository performance can be validated as being correct only by in situ measurements at the repository site. Generic validation efforts on codes and models based on laboratory and field data from other sites may be very useful, but they are not nearly as conclusive as in situ tests at the site of interest. Thus, preclosure monitoring is crucial for the collection of necessary data for performance confirmation.

During the preclosure period, we have opportunities to make both room scale measurements on smaller volumes and remote repository scale measurements on larger volumes. These measurements would be made in situ, so that they would provide the data necessary for validating the conceptual model and predicted processes for performance confirmation at both scales of measurement. On the one hand, the model and the processes could be checked with the actual data and be refined. On the other hand, they also could provide calculations of predicted critical parameter values as a function of time which may be checked against field data, so that the repository operators may be alerted of any anomalous system behavior that should be investigated.

The preclosure period is also a time of large perturbations due to repository excavation and thermal loading by emplacement of the wastes. Therefore, it is an opportunity to investigate the accuracy of performance confirmation models in making predictions over a broad range of critical parameter values and to verify the modeling results. These large perturbations also provide a means to check the accuracy and completeness of the conceptual model and predicted processes.

The entire preclosure period is relatively long, up to 50 years, so that it allows validation of performance assessment models over a significant period of time. During this time, there would also be the opportunity to investigate the presence of slow but important processes that may be difficult to observe in the time frame of laboratory tests (i.e., on a time scale of weeks, up to 1–2 years). Some processes may have slow rates but have a significant effect on the long-term performance of the repository (time periods of decades or longer).

These considerations point out the urgency to obtain adequate baseline data needed for predictive modeling. For all critical parameters, baseline measurements should be made before starting repository construction. This indicates the urgent need for a carefully designed program which integrates the results of many different studies resulting in the development of the necessary baseline database.

Part of such an effort is a well-planned program of data management that incorporates all the field and laboratory measurements of critical parameters. This database will be essential for carrying out the program of preclosure monitoring and performance confirmation which is necessary for the evaluation of the performance of a nuclear waste repository.

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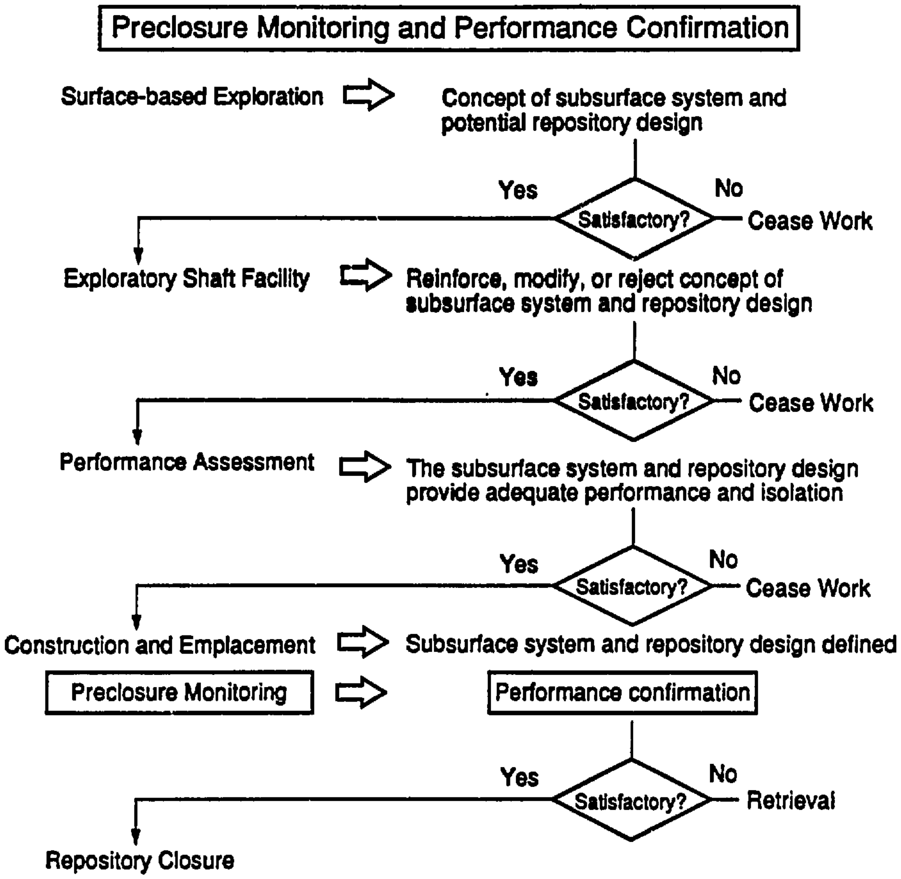

Figure 1. The principal activities and feedback loops required for an adequate and efficient process to generate the knowledge needed to assess the design and performance of a repository. [XBL 892-7460A]

TABLE I. SUMMARY OF PARAMETERS THAT CAN BE MEASURED OR INFERRED: MEASUREMENTS OF DISTRIBUTIONS

(⬤ = strong relation; ● = medium relation; • = some relation; blank = little or no relation)

Critical Parameters	Observables and Measurables (Distributions of Spatial Values)											
	Seismic Velocity	Seismic Atten.	Acoustic Emiss.	Elect. Poten.	Elect. Conduct.	Displacement	Fluid Press.	Temp.	Psychrometry	Liquid/ Gas Tracers	Liquid/ Gas Samples	Radionuclide Concen.
Radionuclide Concentration											⬤	⬤
Liquid/Gas Saturation†	●	●			●		●		⬤	•		
Liquid/Gas Flux/Velocity				•			•	•	⬤	●		•
Liquid/Gas Composition					●						⬤	
Corrosion											•	
Temperature	•	•	•	•	•			⬤	⬤			
Displacement	•	•	●			⬤						
Major Paths (Structure)	⬤	⬤	●	●	●	●	●	●	⬤	⬤	•	•

† The use of neutron logs in boreholes is one suggested procedure for measuring liquid saturation.