MASTER

SUMMARY REVIEW OF WORKSHOP ON MOVEMENT OF FLUIDS IN LARGELY IMPERMEABLE ROCKS

Edited by P. A. Witherspoon

Report from seminars held January 27 - 29, 1977

at

The University of Texas at Austin
Austin, Texas

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The Office of Waste Isolation
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Oak Ridge, Tennessee

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April 1977

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INTRODUCTION

In February 1976, the Energy Research and Development Administration (ERDA) announced a greatly expanded waste management program for defense and commercial radioactive waste. In that announcement, ERDA indicated that the Oak Ridge Operations Office (ORO) of ERDA would have lead responsibility for overall coordination of the expanded geologic disposal program and that an Office of Waste Isolation (OWI) would be created within Union Carbide Corporation - Nuclear Division (UCC-ND) with the responsibility for program management of that activity. The commercial geologic disposal program was named the National Waste Terminal Storage (NWTs) program and represents the principal programmatic effort of ERDA for ultimate and final disposal of commercial nuclear waste.

As part of its expanded activities, the Office of Waste Isolation has organized a series of workshops and seminars on topics such as borehole plugging, rock mechanics, dissolution of rock salt, waste/rock interactions, etc. It is important that these subjects be understood insofar as they might affect the design, safe operation, and long-term containment of a geologic repository.

The report that follows is a review of the OWI-sponsored workshop entitled "Movement of Fluids in Largely Impermeable Rocks." The workshop was held January 27-29, 1977, at the University of Texas at Austin, with the College of Engineering serving as contractor and local host. Dr. Roy Olson, Civil Engineering Department was the conference coordinator, and Dr. Kenneth Gray, Petroleum Engineering Department was the conference coordinator, and Dr. Kenneth Gray, Petroleum Engineering Department, and Dr. Leland J. Turk, Geological Sciences Department, served as consultants. Dr. Paul A. Witherspoon, University of California, Berkeley organized the technical program and served as the moderator.

In the past, considerable research has been carried out on problems of storing radioactive waste in salt formations. As attention shifts to the possibility of using other rock types, such as argillaceous or crystalline hard rocks, it is apparent that additional facts must be obtained in regard to the factors that control the movement of fluids in such formations. The success of radioactive waste storage in these geologic environments will depend on keeping the radioactive materials from returning to the biosphere over long periods of time. In a properly selected site, the porosity and permeability of the intact non-saline rocks should be so small that no appreciable movement through such a pathway will be possible. Thus, the only way in which waste material could reach the biosphere is through fractures in the rock mass.

As a starting point for this workshop, the following general question was posed, "What data base, analytical methodology, and technology are necessary to adequately forecast the physical behavior of a subsurface disposal facility?" The critical consideration was the movement of fluids through fractured rock masses. One must be able to define and control the movement of vapors and liquids through discontinuities, such as faults, shears, joints, and solution channels. This is not an easy task considering the effects of factors such as in-situ state of stress, fracture orientation and continuity, mechanical and chemical rock properties, and perturbations which can occur during the construction and operation of the repository. With this in mind, it was apparent that the success of the workshop, and ultimately the success of the geologic disposal program would require the interaction of a number of disciplines from the engineering and geological sciences. Accordingly, a diverse group of experts was invited (see list of attendees in the Appendix) to attend and participate in the seminar.

The first day of the workshop was devoted to general discussions of selected topics. On the second day, the participants were divided into six working groups, each group being assigned one of the following subjects:

1. Definition and Characterization of the Fracture System
2. In-Situ Measurement of Fluid Flow
3. Effects of Perturbations on the Flow System
4. Role of Numerical Modeling
5. Isotopic and Geochemical Methods
6. Monitoring Programs to Verify Flow System

The reports prepared by each working group were edited to some extent to provide uniformity. The views, opinions and recommendations expressed in this document are those of the authors and are not to be interpreted to be those of Union Carbide Corporation, Nuclear Division, or the Energy Research and Development Administration.

It is hoped that this material will provide the Office of Waste Isolation with a comprehensive review of the state of the art on the problem of fluid flow in largely impermeable rocks and that the recommendations will provide a basis for setting up a successful work program.

TASK 1: DEFINITION AND CHARACTERIZATION OF THE FRACTURE SYSTEM

Committee Members: R. E. Goodman (Chairman), A. G. Duba, N. E. Goldstein,
H. C. Heard, J. F. Howard, R. B. Laughon, I. W. Marine,
R. K. Thorpe

BACKGROUND

The charge to the group was to consider our present ability to measure and define rock fracture networks affecting containment of high level nuclear wastes in mined cavities. Particular attention was directed to crystalline rocks, shales and other nearly impermeable rocks (excluding rock salt, which has been discussed elsewhere) and to identify gaps in our technology and understanding of the various types of fractures at various scale, their degree of connectivity and extent, and their geometrical and physical properties affecting fluid conductivity and storage. We were also to examine methods available to characterize the geometric and physical attributes of fractures, including those that address average properties over large volumes, and those that zero in on detailed descriptions and measurements for individual discontinuities. We were asked to consider what might constitute an adequate description of the fracture system with respect to radioactive waste storage and to indicate the methods most suitable for such a description. We were also asked to recommend fields of inquiry that could improve the descriptive art and propel the waste isolation program forward in a constructive manner. In the limited time available to the panel for exchange of views, it was not possible to prepare a list of best and second best methods. However, it was possible to reach a consensus on areas deserving concentrated study and further development.

Fracture Networks

Discontinuities occur in almost all types of rocks and over an entire spectrum of scales from Angstroms to kilometers. Intra-crystalline defects, such as dislocations and inclusions, are common in almost all rock-forming minerals, particularly those in metamorphically deformed rocks. On a slightly larger scale, fissures are found between the grains and crystals of rocks and as small cracks truncating crystals. These micro-discontinuities, or micro-cracks, are somewhat different from other longer planar conduits in that they can be sampled; that is to say, they can be brought to the laboratory with the core from an exploratory boring. Network studies using electrical analogs show that there is probably a high degree of interconnectivity between sets of microcracks and between individual microcracks and longer planar conduits. Joints, faults and other types of large fractures considered next are not adequately sampled in the average core. These longer discontinuities include potential flow conduits from diverse origins. Stratigraphically engendered joints and partings may create flow paths parallel to bedding. Cleavage and foliation of various sorts derived from parallel orientations of platy or long minerals can create planar parallel conduits in metamorphic rocks. Extension fractures, associated with cooling, folding, uplift and induced tension create rough-walled conduits some of which may be partly or completely filled with hard or soft materials. Distributed shear can produce parallel minor faults, sometimes called "shear joints" or "shear fractures". Flow of cooling volcanic materials can produce "flow banding" with imperfectly connected vugs stretched and aligned in the flow direction. Unloading from deep burial can induce distributed volume expansion causing close fissuring that is commonly seen in granitic rocks. Thermal stresses can likewise induce fissuring, especially in granitic and crystalline carbonate rocks. Selective dissolution

can form planar horizons serving as flow conduits, particularly in impure carbonate rocks having inhomogeneous zones, such as calcareous shales. Finally, natural hydraulic fractures occur due to stoping lava or hydrothermal solutions; these may be almost filled with mineral matter (tight), or imperfectly filled (open). Contacts between formations may present closely fissured or finely jointed rock on either or both sides, due to dissimilar mechanical properties and developed stresses. And finally, minor or major faults and major crushed zones may traverse any type of rock at any depth. Shattered zones may also be found at the contact between intrusives and their host rocks.

Fractures, having diverse origin and size, may be grouped into three general classes: (1) fissures capable of being sampled, (2) recurrent discontinuities, and (3) individual or separable features. The former can be investigated through appropriately posed laboratory experiments. The recurrent discontinuities, frequently called "joints", are necessarily sampled and characterized by means of statistical methods. The individual features, such as pervious contacts, dissolved horizons, crushed or sheared zones, and minor or major faults will be avoided as far as possible; but one type or another will undoubtedly occur in the region near a repository. These would need to be identified, sampled, tested, described and modeled as distinct geological features. There is fair agreement in the literature that many of the narrower discontinuities become less water conductive at depth, due to increase in stress normal to the fracture and corresponding decrease in fracture porosity and permeability. However, some conductive discontinuities extend very deeply, as evidenced by water leakage into deep mines. Therefore, it is extremely important to characterize the relevant properties of discontinuity systems in potential repository sites.

Properties

A number of physical and morphological properties of discontinuities and discontinuity systems affect hydrological properties of rocks. One of the most important properties is the orientation of each of the various sets composing the system. Fracture networks are almost never random; statistical methods are available for tabulating and treating data on joint orientations, although expected statistical distribution functions are many and the subject is by no means closed. Far less is known concerning characteristics of other joint features, including aperture, filling, extent, spacing, interconnectivity and roughness. Even if the rock mass were composed of randomly arranged fractures with identical properties, the rock mass would have directional transmissibility owing to the influence of the state of stress, which greatly changes the conductivity and storage of fractures according to their direction. Finally, the degree to which changing mechanical and thermal stress alters the properties of the rock mass varies from one fracture system to another and also needs to be characterized.

STATE-OF-THE-ART

Methods of Exploration

Since the scale of fracturing is vast, exploration methods on all scales need to be considered in site selection and definition. Aerial photography, and remote sensing from space can be used to locate undesirable major features such as large faults and crushed zones. Data available for this purpose include LANDSAT multi-spectral imagery, and existing low-sun-angle aerial photography. Available handling techniques in addition to visual examination include U.S.B.M. image scanners, and image enhancement by superposition of selected frequency bands to specific features on a regional scale. Such techniques provide capabilities

to detect and project major faults and major shatter zones, and to provide estimates of regional orientations of recurrent discontinuities. In some instances, they also may suggest structural controls on hydrologic flow regimes.

The field of geophysical exploration provides a variety of techniques for obtaining information on fractures ranging in scale from major faults and rock discontinuities, which can be determined from regional surveys, down to individual fractures or fracture systems, which can be resolved by means of borehole and in-situ investigations. Conventional state-of-the-art and novel techniques should be given careful consideration.

On a regional scale, where the study area encompasses hundreds to thousands of square miles, aeromagnetics and regional gravity may provide information on faults, shear zones and certain rock discontinuities that should be avoided, as well as information on apparently uniform crystalline rock terrains which are worthy of more detailed study. In areas of the order of 100 square miles ground magnetics, gravity, active seismic and audio-frequency magneto-tellurics (AMT) are all potentially useful for helping to detect large scale subsurface features, such as faults and rock interfaces, and for aiding in the selection of sites for detailed investigations.

On the site-specific scale of a few square miles, AMT, DC electrical soundings and detailed magnetics can be used to determine the uniformity of rock properties. An area found to contain certain inhomogeneities or anisotropies might be viewed as potentially undesirable. On a yet smaller scale, the borehole provides access to the subsurface for a number of in-hole logging methods and hole-to-surface methods which can help characterize the rock properties in a volume surrounding the hole. In-hole methods such as velocity logging, neutron density logging, acoustic imaging ("Seisviewer"), gravimetry, magnetometry, and

resistivity are several that may be used to obtain a measure of elastic properties, the network of major fractures (joints), regions of anomalous porosity, and discontinuities in rock type. Gravimetry has the capability of yielding crack and matrix porosities averaged over fairly large volumes near a repository site. The potential of this method is yet untested in crystalline rocks.

It is also possible to combine surface and in-hole instrumentation in novel ways to obtain measurements of rock properties radially away from the hole. For example, techniques could be devised which use a seismic, electric, or electromagnetic source or detectors in the hole with arrays of complementary sources or detectors on the surface. Seismic and high frequency electromagnetic wave attenuation studies may have particular usefulness for detecting and measuring the orientation of water-filled cracks between surface and hole, between holes, or from underground caverns. High frequency, broad-band compressional and shear wave seismic sources and receivers would seem to be one possible means for obtaining a three-dimensional picture of Poisson's Ratio, thus showing the principal crack directions averaged over a large volume. The seismic method could also be used in suitable underground openings. Further, from underground openings it may also be possible to obtain the three-dimensional tensor resistivity using orthogonal arrays of transmitting and receiving electrodes. The electric approach should also show the principal crack conductivity directions averaged over a volume of rock.

Borehole logging can provide information about fractures that cross the core, particularly if the core is two inches or larger; however, it is not always possible to distinguish new fractures produced by drilling from older fractures predating drilling unless very careful techniques are employed. Likewise, roughness effects can be inseparable from effects of changing attitudes if the core is small. Triple-tube core barrels should be used,

with a split inner-tube to preserve the relative orientation of the core. In certain cases, oriented core should be obtained by one of a large number of existing techniques. To determine the true appearance of important individual fractures, the method of integral sampling can be tried, in which the core is reinforced before drilling by cementing a reinforcing rod in a concentric smaller hole ahead of the main boring. Borehole television can be used (if the water is nearly clear), as well as acoustic imaging "Seisviewers," mentioned above. Impression packers may also facilitate borehole mapping. To assess the relative importance of discontinuities of different orientations in situ, a multi-armed caliper survey could be conducted inside a packed-off section of the borehole at different water pressures. This would be a novel technique requiring development and demonstration.

Once access to the underground is provided by initial galleries and/or shafts, careful mapping of the exposed rock faces can provide further data on all fracture attributes. The art of taking, processing and interpreting such data can be improved, and a start in this direction would be to log existing mines and chambers. Terrestrial photogrammetry methods, with computer processing and control can provide needed improvements in this art. Such galleries can also provide access for needed measurements of in-situ stress, as can the boreholes drilled from surface or from underground drill chambers. In-situ testing is discussed further by another working group. However, this group re-emphasizes that data on in-situ stresses are highly desirable for characterization of the fracture networks.

Testing

Hydrologic properties of fractures can be assessed by pumping tests conducted in boreholes and on laboratory flow tests conducted on fractured samples. The working group on in-situ testing discussed appropriate tests conducted in the field. Laboratory tests will require samples of fractures,

either undisturbed, reconstituted, or artificially created. The effect of scale needs to be determined definitively, since such basic work is lacking. Fracture flow characteristics under changing normal stress and changing shear stress need to be studied as basic supportive research. Particular lab tests will be warranted, also, as a part of individual site studies. Radial permeability tests can be used to characterize fissure permeability. Tests on fluids of varying viscosity and temperature can assess the influence of environmental variables of interest. Transport of filling material and interaction of filling material with fluids can best be studied in the laboratory and field.

Discussion

In considering how best to characterize the system of fractures for waste isolation in mined caverns, we recognize two distinctly different requirements. We must provide a valid estimation of the overall adequacy of a repository site in advance of construction. And we must be prepared to offer convincing proof, with tangible, believable evidence, that we can predict the long term response. There are several factors to consider. The actual flow regime after canister emplacement can not be measured for permeabilities of the level required until a very long time has elapsed. By itself, a short term, in-situ experiment could definitely negate a site, but it could not unequivocally establish the acceptability of a site for very long-term containment of waste. However, if an in-situ experiment can be coupled with adequate characterization of the fracture regime, and if thorough and physically accurate computer modeling techniques are applied to data, the acceptability of the site could then be examined by means of extrapolations in both time and space scales. Thus, a sound modeling capability is absolutely required for evaluating the hydrologic behavior of fractured rocks. The

accuracy of these computer generated models will have to be demonstrated by means of transient tests of limited scope. The reasons for elaborating what might seem to be axiomatic to some is that it would be far easier if we could avoid the difficulties of providing all the input required for the fractured rock model and proceed directly to an examination of actual fluid flow response.

It was suggested, in our deliberations, that the flow characteristics of a site might be expressible in terms of the shape of a "wetting front" at a given time after filling and pressuring a test chamber. The shape and volume of this fluid volume would reflect the integrated effects of fracture attributes, including orientations and conductivities as well as the state of stress, initial and modified. Chemical and physical tracers, and natural emanations could be monitored to establish the position of the wetting front at a number of monitoring points. However, the length of time required to establish this convinced us that such a proof test would not be possible, as stated above. In summary, we debated the relative merits of going after the components of the flow system independently versus going after the net effect of the flow system through measurement of some measurable response. It was concluded that both approaches are complementary and should be pursued simultaneously.

RECOMMENDATIONS

Though it is realistically impossible to find an unfractured crystalline rock, it should be possible, on the basis of remote sensing and geophysics, to choose a site free from major faults or major crushed zones. Research relating actual fracture characteristics to those estimated from remote sensing would be potentially helpful.

Development of a site must be preceded by borings and by borehole logging and testing. Boreholes of various sizes, from 3" diameter to perhaps 6"

diameter will be required. Borehole techniques and devices will need to be modified or developed for the problems of fracture delineation in small boreholes in crystalline rocks and shales. This problem is somewhat different from the sedimentary rock stratigraphic delineation requirements of the petroleum industry for which most of the downhole techniques were developed. Downhole imaging techniques, such as the acoustic "Seisviewer" and high frequency electromagnetics, may have considerably more potential than currently realized. Downhole gravity should be examined as a means for obtaining fracture porosity values. It will be most productive to apply these devices in regions already logged in great detail below ground. The Hard Hat and Piledriver test sites in the Climax stock at the Nevada Test Site offer an opportunity in this regard.

Borehole caliper technology should be applied to delineation of fractures and possibly to measurement of their apertures. This should be coupled with pumping tests in packed-off sections of boreholes. Characterization of the fracture system in boreholes can also be enhanced by application of radioactive flow meter techniques, such as the "Trace Ejector" method of Birdwell Co. Tracer studies can also be applied to hole-to-hole configurations in novel and productive ways.

Development of numerical modeling capabilities for hydraulics of fractured media near repositories requires extensive input data. The art of gathering and handling these data through statistical methods needs to be improved. Use should be made of existing construction and mining records and available exposed rock faces in mines and chambers. These studies will help assess the possibilities of inferring descriptive data about one part of the fracture length spectrum from observations in another sector of the spectrum, e.g., conclusions on attributes of mega-fabrics from detailed study of micro-fabrics.

Evaluation of the stress regime over the area of influence of the repository is fundamentally important. All applicable methods for doing this under the conditions of the problem should be reassessed, including hydraulic fracturing, overcoring and microscopic fabric analysis. A review of existing knowledge about the state of stress in the crust is being pursued currently and such information as becomes available should be incorporated in the waste management program.

Laboratory research in support of geophysical data interpretation and numerical modeling should be considered an important part of the program. Experiments are needed to develop sampling methods for fractures, to explore the relationship between fracture permeability and stress (normal and shear), to develop means of assessing fracture attributes remotely, and to evaluate other questions. The effect of sample size needs to be assessed. Effects of temperature on properties of fissured and fractured rocks are not well known and should receive laboratory study.

TASK 2: IN-SITU MEASUREMENT OF FLUID FLOW

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BACKGROUND

While sufficient technology exists for the in-situ measurement and interpretation of fluid flow in homogeneous porous media, limited work has been done in discontinuous systems. In a discontinuous system the orientation, spacing and extent of the discontinuities (permeable or impermeable) is of major significance. While in-situ hydraulic measurements may have been made in such systems, little knowledge of the discontinuities (which may or may not exist) was used in the design and interpretation of these tests. A number of individual topics are discussed below and the main recommendations are given at end of this report. However, the group strongly believes that a full-scale evaluation ought to be carried out with all these recommendations integrated to give a meaningful answer to the problem.

There has been considerable discussion as to whether a fractured rock mass must be considered as a discrete fracture system or as an equivalent porous medium (discontinuum versus continuum). It was felt that while this was in many respects the manifestation of a scale effect, not enough is known to generalize about different rock types. Whatever evidence is available points to the direction that in the near field of an opening in crystalline rock the material should behave as a discontinuum and in the far field it could be either an equivalent continuum or a porous medium. Similarly, in softer rocks it is not clear whether the medium behaves as either of the two

classes or indeed as both. It is believed by the group that existing pump test or tracer data should be researched, recompiled, and re-examined, keeping in mind the effect of individual or sets of fractures. It was also recognized that there would be difficulty in obtaining existing data with simultaneous hydraulic testing and fracture mapping carried out in the same hole.

STATE-OF-THE-ART

Withdrawal Tests

In fractured crystalline rocks a withdrawal test typically leads to emptying the well unless a very low rate of withdrawal is used. It was believed by the group that little information is available or known about accurate techniques (surface or downhole) for withdrawal of small amounts of water from boreholes. In softer rocks such as shales, withdrawal from an aquifer either above or below the confining layer with simultaneous measurement of pressure in both materials could be carried out to provide adequate data on the vertical permeability of the fine-grained material. Field methods of determining lateral permeability of fine-grained porous rocks are not readily available.

Tracer Tests

These tests fall primarily into two classes: single borehole dilution method or the two borehole test. While such tests have been used in open boreholes for porous media flow evaluations, little work has been done in packed-off sections of fractured rock along with accurate fracture mapping. It was felt by the group that these tests are important in that they may provide a direct measurement of velocity. Other parameters, such as permeability and dispersion coefficients, can also be evaluated from the tests. It was suggested that the mapping of groundwater temperatures may be useful in defining the flow system and ought to be investigated in more detail.

Injection Tests

It was generally agreed by the working group that current technology in steady/non-steady tests is sufficiently developed but its application to fractured rock masses needs further refinement. A major effort ought to be made to obtain highly sensitive downhole pressure and flow transducers that do not suffer from high line loss and/or temperature effects. A detailed evaluation of the long-term stability of "frequency type" instrumentation is needed.

In fractured systems where multiple sets of fractures exist, the importance of the alignment of the test borehole with respect to the fracture sets was emphasized. Wherever possible, orthogonal intersection of the test section and the fracture sets ought to be attempted. Failing this, the use of flow linearizers which hydraulically isolate fracture sets should be investigated. The importance of this alignment effect in systems where multiple fractures play an important role has been investigated.

Pulse Injection

Pulse testing has been used in porous media from well to well where very low permeabilities and porosities are encountered. This method has not, to the group's knowledge, been thoroughly investigated in fractured systems. It is suggested that experiments be tried to test what could be potentially a useful technique. This technique should be extremely useful for measuring permeability of shales because only a pressure pulse, rather than the fluid, is transmitted through the formation. Thus, only short-term tests would be required. Similarly, an evaluation of this technique for a single borehole should be made. If this technique can be used successfully in fractured rocks, it will be a powerful tool for evaluating the hydraulic properties of these rocks.

In-Situ Stresses

It was felt by the group that the role of in-situ stresses is vital to understanding fluid flow in largely impermeable media. It was further felt that the hydraulic fracture technique provides an adequate measure of this parameter. However, in the entire United States only a limited number of stress measurements (magnitude and orientation) have been carried out below 500 m by hydraulic fracturing, and therefore, the existing data base is small.

Piezometers

The group agreed that one must know the distribution of fluid pressures within the rock mass and suggested that this could be accomplished by installing multiple point piezometers in observation holes in the general area. It is also worthwhile to install multiple point piezometers around boreholes that are being water tested. These piezometers ought to be essentially of the transducer type as discussed under the subsection on Injection Tests.

RECOMMENDATIONS

Field Studies

In addition to the suggestions given above, the working group believed strongly that techniques for measuring fluid flow and those parameters that affect fluid flow need to be evaluated under in-situ conditions over a scale of depths similar to that of the repository. Table 2-1 outlines the various parameters that need to be measured and the corresponding techniques that we recommend be evaluated to determine their suitability. These measurements and tests need to be evaluated at the same time in the same location. The use of an existing mine complex offers a potential test

area. The existing mine galleries and adits would be used to measure the geology and the properties of existing discontinuities (joints, fractures, bedding planes, faults). New adits would be driven and boreholes cored from the adits for near field measurements need to be conducted over the range of depths from the near surface to potential repository depths.

Table 2-1 Parameters to be measured and corresponding techniques to be evaluated.

Measurements	Techniques
1. In-situ stress (free field (near field	hydrofracing, overcoring, etc.
2. Original potential field	piezometers
3. Permeability and velocity microscale (matrix) single joints multiple joints areal	{ injection tests tracer tests pulse tests
4. Fracture mapping	{ geologic mapping oriented core geophysical techniques (TASK 1)
5. Porosity/storage	injection/withdrawal tests
6. Matrix properties	laboratory tests
7. Temperature field	temperature probes and geophysical logs

A sketch of a potential test area is shown in Figure 2-1 and the recommended sequences of tests are outlined below:

1. Tests need to be conducted in the far field before new adits are driven.
2. Tests need to be conducted in front of the face and in the surrounding rock during excavation of the adit.
3. Tests need to be conducted in the adit and surrounding rock after the adit is driven.

Figure 2-1. Diagrammatic Sketch of Mine Complex
(horizontal scale schematic)

4. Sequential List of Evaluation Steps

- a. Find mine
- b. Map surface
- c. Map mine and adits
- d. Install piezometers
- e. Stress in freefield
- f. Pump, pulse, tracer tests in boreholes
- g. Pilot borehole for adit and testing program - verify predictions
- h. Construct adit and new boreholes
- i. Perturbations of temperature and pressure
 - ventilation tests
 - heater tests
 - flatjack tests

Laboratory Studies

It was believed by the working group that laboratory studies should be carried out to supplement in-situ measurements. The following items are considered important:

1. Determination and verification of stress-permeability relationships on individual basis:

$K_f(\sigma)$, $K_f(\tau)$, $K_f(T)$; σ = normal stress, τ = shear, T = temperature, K_f = hydraulic conductivity.

2. A cross-coupling of the above terms and time effects.

Note: Items 1 and 2 should be tested for multiple fractures. Further, the sample size-effects are of importance and should be examined.

3. Injection tests with different packer spacing should be carried out in the above test configuration. This testing will shed light on scale effects under controlled tests.
4. Investigate the effects of aperture size, fracture geometry, stress and temperature on groutability of fracture systems.

Miscellaneous Ideas

It was suggested by the group that alternative ideas should be investigated to examine important parameters in defining the flow through fractured systems.

1. The pressurization of boreholes at depth with simultaneous surface measurements of tilt, resistivity, etc.
2. Injection of pressurized inert and harmless gas at depth and simultaneous surface detection by an array of detectors.
3. Injection of salt solutions in existing fractures and resistivity measurements prior and subsequent to the injection.

TASK 3: EFFECTS OF PERTURBATIONS ON THE FLOW SYSTEM

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BACKGROUND

Assuming a site that possesses the appropriate virgin flow and other conditions for an underground repository for the isolation of radioactive wastes can be found, it is necessary to assess the effects of all subsequent perturbations, from actual exploration through excavation and operation to long-term geologic, tectonic and climatic changes on the continuing integrity and safety of the repository.

It is convenient to consider these perturbations during each of five different periods of time, based upon that period of time within which the different kinds of perturbations are likely to be dominant. For the first repository, some additional experiments and monitoring may be required to validate certain aspects of design and construction, and ease of access may also be necessary. Under these circumstances, the five periods of time are as follows:

1. Excavation and construction 0 - 5 years.
2. Monitoring and initial emplacement with easy access (open excavations) 0 - 20 years.
3. Major thermal loading caused by the dissipation of energy from wastes, 20 years - 100 years.
4. Short-term containment when the strong thermal gradients attenuate, 100 years - 1000 years.
5. Long-term containment when tectonic, geologic and climatic changes may occur, 1000 years - 1,000,000 years.

Changes in the strains and stresses in the rock from the virgin conditions originally prevailing at the site must be expected as a result of these different perturbations, shown for each of the five time periods in Table 3.1.

STATE-OF-THE-ART

In general, mining excavations are designed to stand up only as long as is necessary to extract the ore. To design them for longer periods of stability than this would incur unnecessarily higher cost or sterilization of ore reserves. Centuries of experience, guided in recent decades by the science and practice of rock mechanics, have resulted in most mining excavations being built to suit this purpose nicely, and many of them collapse over a period of days to years following active mining. Mining practice and methods therefore set useful guidelines concerning the minimum requirements for the stability of underground excavations in the short-term. Some mining excavations, such as shafts and service excavations in the vicinity of shaft pillars, are designed to remain stable and serviceable for many decades, but there are documented instances where these have proved to be inadequate for this purpose. This vast body of empirical and theoretical knowledge can be used to great effect in laying down guidelines for underground excavations which must remain stable for much longer periods, say centuries at least. For waste repositories the guidelines must reduce the risk of failure by many orders of magnitude, compared with the risk normally accepted in mining or even civil engineering practice. It seems reasonable to expect that changes which decrease to a very low level the risk of failure or instability of an excavation occurring within a century are likely to be at least as effective in achieving comparable reduction in risk over much longer periods of time.

Table 3.1 The Effects of Perturbations on the Flow System

T I M E (Y E A R S)

Perturbation	0 - 5	0 - 20	20 - 100	100 - 1000	1000 - 1,000,000
Rock Strain and stresses	Induced by excavation	Minor decrepitation	Thermal strains, stresses	Heating of Site, cooling of repository	Tectonic geologic, and climatic loads
Fractures	Excavation (filled or void) comprises major conduits and sinks connected to surrounding rock by pre-existing and induced fractures	Fracture zone develops and extends around the excavations	Unknown variety of major new fractures may develop	Time-dependent fracture propagation	New fractures caused by tectonic, geologic, and climatic changes
Flow	Excavations are a sink for transient flows from the surrounding rock and conduits for flow through the excavations	Slight increases in the size of flows and fractures into the excavations	Major increases (10^3) in the volume of rock connected to excavations may occur	Flows decrease but remain higher than in virgin conditions Convective and thermochemical phenomena occur	Changes in tectonic, geologic, climatic, loads may alter flows and pore pressures

In hard rock, experience shows that significant degradation of the surface of relatively long excavations of roughly equi-dimensional cross-section, such as tunnels and large boreholes, occurs when the field stress in the rock through which such an excavation passes is about a quarter of the uniaxial compressive strength of the rock. Therefore, excavations of this geometry which are expected to be stable for long periods of time must be constructed in rock where the field stress is only, say an eighth of the uniaxial compressive strength of the rock. This imposes a limitation on the depth of the excavation; for hard rocks, with a uniaxial compressive strength of about 200 MPa (29,000 psi), the maximum depth should not be more than about 1000 m (3,300 ft).

In mining, also, it is well known that adjacent excavations interact with a deleterious effect on one another if their center-to-center spacing is less than three times their width. Over long periods of time the sides of an excavation may deteriorate, thereby effectively increasing the size of the excavation and decreasing the center-to-center distance between them, which will aggravate such deterioration. To obviate this problem, it is suggested that the center-to-center space of the excavations for a repository should be increased to ten times their width, resulting in an areal excavation of 10 percent.

Undoubtedly, the cheapest method of excavation in hard rock is by drilling and blasting. However, conventional drilling and blasting usually results in considerable damage to the rock around the excavation. This damage can be minimized by techniques such as post-splitting, but mechanical boring of most hard rocks, especially those containing less than about 60 percent quartz minerals, is now practicable. Mechanical boring is, therefore, a preferred method of excavation for waste repositories, because it reduces to a minimum

the perturbation resulting from the processes of excavation.

The integrity of the rock around excavations should be preserved by good support or rock reinforcement. Rockbolts and their like, with lacing, wire mesh, and shotcreting are regarded currently as the best methods of support for tunnel-like excavations in hard rock. However, the presence of holes for rockbolts radiating from such excavations may be undesirable in the case of an underground repository, even if the rockbolts are grouted into their holes. Nevertheless, since the initial excavations may have to remain open for several years to facilitate monitoring and retrieval of the waste if necessary, it is recommended that systematic bolting, lacing, meshing and shotcreting be used as primary support. Probably the rockbolts should be only a meter long, with a slightly smaller center-spacing, unless special rock conditions call for longer bolts. Shotcreting is not only an important component of this support system, but also it protects the rock surface from weathering and retards the ingress of water into the excavation from the rock mass.

There can be no doubt that complete back-filling of excavations is the best form of support and one which will be necessary anyway in all probability. It is the only form of support which can enhance the stability of excavations and decrease the probability of major fractures resulting from them in the long term, say, a century and more. However, it should be borne in mind that even the best back-fill, placed pneumatically at high velocity with cement has porosities of about 20 percent, so that even filled excavations will constitute conduits for liquids and gases. Nevertheless, rock fracture is always accompanied by dilatation and the filling of voids precludes such expansion of the rock into the excavation, thereby inhibiting fracture formation, especially in the long term.

Pre-existing or induced fractures encountered during excavation will have to be treated to reduce their transmissibility, if indeed they do not rule out the use of the site anyway. Current technology for doing this involves grouting. In essence, grouting works by filling the voids in a fracture. Deformation of the rock always tends to be concentrated across any weakness, particularly fractures, whether they are grouted or not, so that grouted fractures open readily as a result of deformations subsequent to grouting. The flow around and away from a repository will be determined in a very large measure by both the excavations themselves, whether filled or unfilled, and by any fracture systems in the rock mass at the site. A suitable site is likely to have either no fractures or impermeable fractures. Methods of design aimed at minimizing induced fracturing have been discussed already.

One of the features unique to an underground nuclear waste repository is the generation of relatively large amounts of heat several years after the emplacement of the waste. Though these issues are poorly understood at present, the facts that temperatures are expected to be about 200°C and that the coefficient of linear thermal expansion of rock is of the order of 10^{-5} indicate that thermal strains of the order of 2×10^{-3} are likely to be generated in the rock around the repository. This may prove to be one of the major perturbations to which the repository and the rock mass at the site will be subjected in the foreseeable future. It is therefore vital that the effects of this perturbation be analyzed in detail and with confidence before any reliability can be attached to the design of a repository in hard rock. This leads to the conclusion that experiments and investigations into the thermal properties and behavior of rock with a view to gathering the data necessary to predict the effects of such heating

on the initiation and propagation of fractures in the rock around the repository are vital.

RECOMMENDATIONS

The first and most important recommendation is that research and investigation into the behavior of rock in response to thermal loads is necessary, so as to enable the effects of heating by the radioactive wastes and the probably thermally-induced fracturing which may result from such heating to be evaluated quantitatively and with confidence.

Next, it is suggested that whatever information is collected about a site beforehand, the most reliable and valuable information will become available only as actual excavation progresses. Therefore it is recommended that the initial design and planning be highly flexible so that data which become available during excavation can be taken into account, even if this involves major changes to the original design, such as changes in the orientation and the depth below surface, of the excavations. In fact, careful observations and suitable testing must be considered as an integral and concurrent part of the whole operation of excavation, which are every bit as important, if not more so, than those in the stage of exploratory investigations.

The best techniques available for the design, excavation and reinforcement of the repository excavations should be used at every stage. In addition, it is recommended that systems for monitoring strains, the movement of water and pore pressures, rock temperature and crack propagation over long periods of time, say, up to 100 years, should be an integral part of the design and planning of the project. Also, it is recommended that serious consideration be given to implanting suitable tracers in parallel with the waste. These should be released at specific times after emplacement and used to detect

any unexpected mobility of material from the position of the radioactive waste containers.

Finally, a system for detecting any precursive indications of major tectonic, geologic and climatic perturbations and assessing their effects on the integrity and safety of the repository should be established.

TASK 4: ROLE OF NUMERICAL MODELING

Committee members: J. O. Duguid (Chairman), G. E. Barr, J. D. Bredehoeft, R. G. Charlwood, U. E. Lindblom, G. F. Pinder, J. P. Sauty

BACKGROUND

The working group considered the problem of transport of chemical species and heat through fractured porous media under dynamic stress loading associated with emplacement of high level radioactive waste in largely impermeable rocks. The period of analysis considered in simulating the behavior of the waste-rock system can be divided into four time periods based on the phenomena considered. These periods are the virgin system, the construction period, the short term and the long term. The short term is considered to extend from the end of construction to 1,000 years; a period in which the waste rock interactions are the most severe. This is also the time required for decay of most of the fission products. The long-term is considered to extend from thousands of years up to perhaps 1,000,000 years; the effects are associated with (1) groundwater transport of actinides during 10 or more halftimes and (2) far-field disturbance due to thermal transport. The major processes that occur during the four time periods, whether they are transient or steady state, and an indication of their significance is given in Table 4-1.

The basic type of model needed for simulating each major phenomenon was also considered. The consensus of the working group was that the medium could be treated as a large scale overlapping continuum for simulations of the virgin processes and the long-term effects. However, for simulation modeling during the short term period, deterministic models of the actual

fracture networks must be used to predict effects near the boundary of the repository. The need for deterministic modeling arises because the assumption of a continuum of fractures is violated near the boundary of the repository.

STATE-OF-THE-ART AND RECOMMENDATIONS

The evaluation of the availability of field equations, constitutive laws, solution procedures, and the capabilities for data measurement are given in Table 4-2 for the problem areas of Table 4-1. Table 4-2 indicates a complete lack of understanding of the short term coupling of thermal, chemical, and mechanical processes near the repository where the largest effects of the waste-rock interactions will occur.

The group identified the following areas where work should begin as soon as possible:

1. The development of technology to measure single fracture and fracture system properties (effective porosity, permeability, etc.).
2. The definition of the source kinetics (5.3, 5.4*).
3. Evaluation of the sorption coefficients (2.4).
4. Formulation of the coupled set of thermal, chemical, and mechanical equations for simulation of short term effects of waste-rock interactions (2.3, 3.3, 4.3).

Other specific topics that must be investigated relate to the worth of data obtained from field and laboratory tests. Numerical models should explicitly incorporate the uncertainties in data to show the uncertainty in the simulated results. Research efforts can then be directed toward improved data gathering methods for those parameters that have the most influence on the simulated results.

*numbers refer to matrix locations in Table 4-1.

Table 4-1. Brief Description of Problems

T I M E (Y E A R S)

	VIRGIN	0 - 30 CONSTRUCTION	30 - 1000 SHORT TERM	1000 - 1,000,000 LONG TERM
FLUID FLOW	STEADY 1.1 Regional flow field. ²	TRANSIENT 1.2 Flow into the excavation. ² Impact of grouting. ¹	TRANSIENT 1.3 Air intrusion into host rock. ²	STEADY 1.4 Regional fluid forecast. ² Climatic changes (i.e., glacera- tion, erosion, tectonics). ²
SPECIES TRANSPORT	STEADY 2.1 Regional geochemistry. ²	2.2 Impact of grout on geo- chemistry. ¹	TRANSIENT 2.3 Thermal degradation of rocks (phase and mineralogy changes). ² Chemical diffusion. ²	TRANSIENT 2.4 Chemical diffusion & dispersion from source (sorption & recon- centration). ²
ENERGY TRANSPORT	(Not applicable)	3.2 Drying of cavity by air circulation. ¹	TRANSIENT 3.3 (Convection & Diffusion) - Two Phase convective diffusive transport in cavity and immediate vicinity. ³	3.4 Thermal modification of flow field. ¹
COUPLING STRESS	4.1 In-situ stress field as related to fracture per- meability tensor. ¹	4.2 Local fractures (induced by excavation). ³ Change in rock properties (effects of rock bolting and mining sequence). ²	4.3 Thermally induced stress and creep. ²	(Not applicable)
SOURCE KINETICS	(Not applicable)	(Not applicable)	5.3 Species and source kinetics Glass kinetics and dynamics (possibly not attainable by modelling). ³	5.4 Species and source kinetics. Glass kinetics and dynamics (possibly not attainable by modelling). ²

¹significant; ²more significant; ³most significant

Table 4-2. Availability of Simulation Models

TIME (YEARS)

	VIRGIN	0 - 30 CONSTRUCTION	30 - 1000 SHORT TERM	1000 - 1,000,000 LONG TERM
FLUID FLOW	¹ Exist ² Exist ³ Exist ⁴ Yes for continuum ⁵ Possibly for discrete fractures	¹ Exist ⁵ ² Exist (assuming grout already emplaced) ³ Exist ⁴ Unknown	^{1, 2, 3, 4} Don't exist	^{1, 2, 3} Exists (continuum models) ⁵ Some information exists ⁶
SPECIES TRANSPORT	¹ Exist ² Known in part ³ Under development ⁴ Appear feasible (some data exist).	¹ Exist ² Exist (assuming grout emplaced) ³ Exist ⁴ To be refined	¹ May exist ^{2, 3, 4} Don't exist	¹ Exists ² Don't exist ³ May exist depending on problem ⁴ Don't exist
ENERGY TRANSPORT	(Not applicable)	¹ Exist ² Standard mining ventilation codes exist. Additional development needed. ³ Exist to required level of accuracy ⁴ To be experimentally determined	^{1, 2, 3, 4} Don't exist	^{1, 2, 3, 4} Exist
COUPLING STRESS	^{1, 2, 3} (Not applicable). ⁴ Feasible	^{1, 2} Exist ³ Are Available ⁴ Well developed	¹ Exist for some situations, ^{2, 3} Exist for above subset ⁴ Some techniques available	(Not applicable)
SOURCE KINETICS	(Not applicable)	(Not applicable)	^{1, 2, 3, 4} Don't exist	^{1, 2, 3, 4} Don't exist

¹Field equations
²Constitutive laws
³Solution procedures
⁴Data measurement

⁵Simulation of grout emplacement may be important
⁶Uncoupled systems only, additional work required
⁷Fracture propagation relatively unknown

⁸Some estimates are probably available, additional work necessary. Seismicity, tectonics, and climatic changes need work.

TASK 5: ISOTOPIC AND GEOCHEMICAL METHODS

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BACKGROUND

There are several scales on which geochemical and isotopic studies are useful. On the regional scale, if enough sampling points (boreholes, mines, natural discharge and recharge points) are available, the general major ion chemistry of the water can be useful. Patterns of chemical change as displayed on trilinear diagrams and hydrochemical facies maps show water flow direction and may indicate the degree of interconnection among aquifer systems.

On a more sophisticated level, geochemical quantities, such as saturation levels with respect to aquifer minerals, may qualitatively indicate relative water residence times. These saturation levels, with ratios of the stable isotopes of carbon and sulfur, can be used to validate models of the progress of reactions between water and aquifer. Such models are needed, for example, to derive water ages from carbon-14 (^{14}C) and will be needed if U-disequilibrium is to become a successful water dating method.

Deuterium (D) and oxygen-18 (^{18}O) are stable water isotopes that are also frequently of interest in regional studies. They may give further information about recharge areas and conditions, the thermal history of the water mass, and certain chemical reactions.

On a local scale, artificial tracers are useful in characterizing the fluid flow field in and near boreholes. They can also be used to measure such aquifer properties as effective porosity, dispersivity, and distribution coefficients (K_d).

STATE-OF-THE-ART

There are several prerequisites to the use of isotopic and geochemical methods. First, it must be possible to collect samples of sufficient size and quality. As formations become less permeable, the ability to apply these techniques decreases simply because the formation does not yield enough water to analyze. Second, proper sampling techniques and reliable analyses must be done. Samples collected in buckets, stored in Mason jars, and analyzed by a second-rate laboratory provide no useful information. Design of a formation fluid sampling program must go hand-in-hand with the design of all other aspects (hydraulic testing, rock property testing, etc.) of a site evaluation plan.

Table 5-1 lists a selection of possibly important constituents and describes some of the constraints on the problem of field sampling.

Borehole Sampling Considerations

Borehole sampling is most successful when integrated with the hydraulic testing program. Hydraulic testing may be organized with such phases as:

1. Well development, including surging, swabbing, etc.
2. Specific capacity (pumping) tests
3. Rest water levels, after pumping
4. Injection testing, including slug tests, tracer tests, etc.

Geochemical sampling should be done after as much fluid as needed for the hydraulic testing has been withdrawn, but BEFORE any water has been injected, i.e. between steps 3 and 4, above.

There is little point in doing more than elementary analytical work on samples not truly representative of the formation fluid. Thus, the drilling method, borehole preparation for testing, and method of delivering the fluid to the surface sampling point should be designed to minimize contamination of the formation fluid.

Table 5-1. Water constituents of possible importance in isotopic and geochemical methods.

CONSTITUENT	SAMPLE VOLUME (liters)	REMARKS
<u>Chemical</u>		
Major anions: Cl^- , $\text{SO}_4^{=}$, etc.	$10^{-2} - 10^0$	
Major cations: Na^+ , Ca^{+2} , etc.	10^{-1}	Filter and acidify.
Carbonate species: HCO_3^- , $\text{CO}_3^{=}$	10^0	Field pH and alkalinity analysis.*
Sulfide species: H_2S , HS^-	10^{-1}	Field analysis or fixing.*
Trace metals	10^0	Filter and acidify.
Gases: He, Ar, H_2 , CH_4 , etc.	10^0	Gas tight collection vessel required.*
<u>Stable Isotopes</u>		
H/D, ^{18}O , ^{16}O	10^{-2}	
$^{34}\text{S}/^{32}\text{S}$	$10^{-1} - 10^1$	
$^{13}\text{C}/^{12}\text{C}$	10^0	Field fixing.*
<u>Radioisotopes</u>		
^3H	$10^{-1} - 10^0$	*
^{14}C	$10^2 - 10^3$	Field concentration.*
$^{234}\text{U}/^{238}\text{U}$	$10^1 - 10^2$	Field fixing.

Note: * - Sample cannot have been exposed to air before collection.

Drilling Methods

The drilling medium should invade the formation and/or react with the fluid as little as possible. Air drilling is best, although air may invade the formation and be difficult to remove before withdrawing a fluid sample. The lower air pressure used, the less invasion possible. Development of reverse

air drilling technology would be useful. Percussion drilling has been used, but removal of the highly reactive rock dust from the hole before sampling is difficult.

Borehole Preparation for Testing

To characterize a system, vertical variation in chemistry is important, so samples from known intervals are taken. This involves sampling below a single packer as the hole is drilled or between packers in a completed well. Leakage around packers can usually be interpreted from pressure effects. After sampling, injection tests containing radiotracers may be made. Detection of the tracer above or below the packed interval indicates leaking and the samples previously taken from the interval are discarded or marked as suspect.

Cement is highly reactive with water and remains so for periods of years. The borehole sampling program must be designed so that no sample can possibly have come in contact with cement.

Delivery to Surface

The sample must reach the surface sampling point with no exposure to air and, ideally, at formation pressure. This means a positive displacement pump placed at the level to be sampled (between two or below one packer) is needed. The interval is pumped continuously (at a rate known from the previous specific capacity tests to be below the yield) and tested for pH, temperature, and electrical conductivity until all three are steady. Then, presumably, representative formation fluid is being delivered and sample collection begins.

Pumps

A major equipment need is for a small diameter (< 3 inches), positive displacement pump that is powerful enough to be used to pump water up several thousand feet of hole. Such a pump should be operable at a variety of flow rates. In fractured rock with a very low yield, low pump rates will be required, and the pump should be able to operate between or below packers. A

thief sampler which could deliver at least 1 liter of fluid at formation pressure could be useful in some cases. Apparently, such a device has been developed at Lawrence Livermore Laboratory, however its applicability to this problem has not been determined.

Tracer Techniques

Tracer techniques are used to determine effective porosity, groundwater flow velocity and direction, dispersion coefficient and values of K_d in the field. Three techniques are usually used for field studies: borehole tracer, single-well tracer, and multi-well tracer.

Borehole Tracers

Locations of fractures can be determined from borehole geophysical logs. Whether the located fractures are water-transmitting or not can be determined by borehole tracer techniques. This technique is to inject a gamma-emitting radioactive isotope into a packed-off section that contains fractures. The section can be stressed by adding or withdrawing water from the borehole. The water-transmitting character of the fractures can be determined from movement of the isotope. If the system is tested under static conditions, the borehole tracer method can also indicate whether vertical cross-flow exists at certain depths. Borehole tracing is commercially available and commonly used in determining water-transmitting fractures.

Single-well Tracer Tests

In the early stages of selecting a site, few boreholes will be available and it will be desirable to obtain as much data as possible from a single borehole. Flow direction, velocity and effective porosity usually can be determined from the single-well tracer method. To determine flow direction, a small quantity of gamma-emitting radioactive isotope is injected at a desirable depth, then a single-window detector equipped with compass direction rotates around the well at the injection depth to map the concentration of gamma energy which will

indicate the direction of the flow. If a slug of water tagged with tracer is injected at a desired depth, natural flow intercepted by the well will dilute the tracer concentration in the well. From the history of dilution, groundwater velocity can be estimated. A large amount of water tagged with tracer can also be injected into the aquifer through the well. The well can be pumped either immediately after injection or after the injected water body has moved away from the well by natural groundwater flow. In either case, the effective porosity of the aquifer and natural groundwater flow velocity can be estimated from the concentration of tracer observed in the pumped water, the injection and pumping rate, and sampling time.

Multi-well Tracer Tests:

If there is more than one well at a site, then multi-well tracer tests will yield more information than single-well tracer tests, including dispersion coefficients, K_d s, and first arrival time, which is an important consideration for waste-contamination prediction.

Multi-well tracer tests can be made either under artificial stress conditions, that is, pumping or pumping and injection simultaneously, or without artificial stress. Under either condition, water tagged with tracer is injected into one of the wells located at an up-gradient direction, and the concentration of tracer in waters obtained from observation wells is observed for a certain time period. A breakthrough curve of tracer concentration versus time can thus be constructed. First arrival time, dispersion coefficient, and average flow velocity can be estimated from the breakthrough curve. If the injection water is tagged with multiple tracers, and one of them is a conservative tracer, that is, a tracer such as tritium (^3H) that moves with the water particles, then the K_d of a specific tracer in the specific field situation can be estimated from the breakthrough curve of that tracer.

Both single- and multi-well tracer methods are developed on the basis of flow through porous media, however, very little work has been done to use these tests in fractured rocks. It is important to find out whether these methods are also workable in fractured rocks.

Strong field evidence indicates that dispersion coefficients determined in the field are much higher than those determined in laboratories, e.g. several hundreds of feet versus a few inches. Field evidence also suggests that laboratory K_d s are higher than those observed in the field. For example, the laboratory K_d of cesium-137 (^{137}Cs) in shale is high, therefore, it was believed that ^{137}Cs could move only a few feet in shale. However, at ORNL it was found that ^{137}Cs has moved down to 150 feet in shale as detected in a well which intersects fractures. The K_d of strontium-90 (^{90}Sr) determined in laboratories usually is also high. However, a field value for K_d of ^{90}Sr found in the Snake River basalt aquifer in Idaho is only 3. In view of this evidence, it is strongly recommended that further study to determine K_d in the field should be made, especially in fractured rocks.

In conclusion, tracer techniques are powerful tools to determine aquifer characteristics as well as fluid characteristics at a specific site and are therefore important in the selection, design and monitoring of a waste repository. During mining excavation and construction, tracer methods probably also can be used to determine the source of water which moves into the underground opening.

Radioisotopes

Most natural or environmental radioactive isotopes in hydrogeologic systems are geochemical tracers and therefore reflect the geochemical history of a given water mass. Their abundance is not only controlled by their decay with time but also those processes which affect the chemical composition of the water. If attempts are made to obtain information about water residence times from

their abundance in aqueous compounds, then the geochemistry of the element under consideration has to be investigated in parallel with "age-dating" activities.

This dependence on geochemical processes severely limits the usefulness of many potential tracers for practical, applied problems. At present only tritium (^3H) and carbon-14 (^{14}C) are widely used and there is some hope that uranium isotopes ($^{234}\text{U}/^{238}\text{U}$) may provide an additional tool. This is true whether one wants to obtain absolute "water ages" or flow velocities. The information obtainable from radioisotope investigations is thus dependent on (a) an understanding of the geochemistry of the hydrologic system under investigation, (b) the number of samples which can be obtained, and (c) the location of the sampling points.

The three are interdependent since the geochemical and isotopic history of a water sample can be elucidated only incompletely from a single sample. For example, it is possible to calculate maximum ages from ^{14}C contents measured on a single sample but if flow velocities are to be determined, measurements at at least two points are needed.

Furthermore, it has to be kept in mind that "velocity" determinations in a relatively dry crystalline complex measured on samples obtained from a relatively undisturbed system may or may not reflect the "velocity" distribution one will get after mining has been initiated and the system has been put under stress. For this reason we recommended that isotope and geochemical investigations should not be limited to the potential disposal sites but should also be carried out in existing underpressured openings such as mines, powerdam developments, etc.

Tritium:

Tritium has a half life of only 12.26 years and is therefore not suited for the investigation of old hydrogeologic systems. However, it is a "conser-

vative" isotope since its abundance in subsurface waters is virtually independent of geochemical processes. It is not produced within the rock masses and has only a meteoric origin. Therefore if it occurs in measurable amounts ($> 1\text{ TU}$) in groundwaters, then this is an indication that the water mass sampled has a modern component. For a sample collected in a core in fractured terraines this indicates either very active flow through any number of fractures or reflects contamination from drill fluids if drilling was done with water.

Carbon-14:

The geochemistry of carbon and its isotopes has been investigated extensively in many different groundwater systems and geochemical model calculations are fairly well advanced. It is thus possible to obtain meaningful information from ^{14}C studies if the isotope analyses, which have to include determinations, are complimented by geochemical data of high quality and if interpreted in conjunction with information obtained from hydrogeologic studies. Without such additional data the ^{14}C content of the aqueous carbonate permits the determination of maximum age only. This in itself may be very useful and, therefore, ^{14}C dating should be done even in investigations during which only very limited sampling is possible.

Wherever the presence of ^{14}C in water does reflect a certain amount of water movement the absence of it does not necessarily imply that it has decayed with time below detection-limit. Radioisotope measurements are absolute measurements (as opposed to the relative ratio measurements done for stable isotopes) and therefore any dilution of the original ^{14}C content by ^{14}C free carbon will affect the count rates. Such dilution (or loss) may come about through the dissolution and isotope exchange processes with carbonate rocks or addition of carbon dioxide to the flow system from other inorganic or organic processes. Such processes affect the ^{13}C contents of the aqueous carbonate and the ^{14}C

determinations. Correction and adjustment procedures have been developed and are based on chemical and ^{13}C data. In systems which are geochemically well understood, water ages up to 35,000 to 40,000 years can be determined with some confidence.

Uranium Disequilibrium

The decay of uranium isotopes into other elements not only provides a potential age dating tool but their abundance in water and rock matrix also yields much information about the geochemistry and flow rate of water moving through rocks. For example, the recoil which occurs during the decay of uranium-238, ^{238}U , to ^{234}U causes structural damage in the immediate vicinity of the decaying nucleus and thus results in a preferential leachability of ^{234}U . The degree of this leaching will depend on the geochemical and hydrologic characteristics of the aquifers.

^{234}U is commonly present in groundwater in excess of its equilibrium value with its parent ^{238}U . The decay of this excess to the equilibrium $^{234}\text{U}/^{238}\text{U}$ ratio occurs with the half life of ^{234}U (250,000 years). If the geochemical behavior of U in groundwater systems were better known, it is probable that U-isotope ratios could be used to estimate velocities in slowly moving groundwater. By analogy with the development of the ^{14}C interpretation methodology, U-isotope interpretation could be improved by field studies in otherwise well characterized aquifers.

Stable Isotopes

Water Isotopes

Stable isotope studies involve the isotopes of hydrogen (D/H) and oxygen ($^{18}\text{O}/^{16}\text{O}$) which are an integral part of the water molecules. They are ubiquitous and only their absolute abundance varies as a function of climatic parameters in the infiltration areas and with the origin of the vapor masses from

which a given groundwater originates. In the low-temperature groundwater environment, these primary concentrations remain constant and are not affected by chemical, physical or biological processes; i.e., the stable isotope ratios of a groundwater is a conservative property of water. However, if the water were subject to evaporation before infiltration, or became part of deep circulation systems where isotope exchanges occurs at elevated temperatures, or micropore filtering through "clays" has taken place, then isotopic changes may occur. However, such changes do not necessarily affect the ^{18}O and D to the same degree and therefore such changes can normally be recognized and evaluated.

An important aspect of stable isotope studies in hydrologically old systems is the dependence of ^{18}O and D concentrations on climatic parameters. Thus the dramatic climatic improvement which occurred approximately 10,000 years ago led to significant isotope changes in the precipitation at some localities. Under favorable circumstances such isotope shifts may be preserved in groundwater systems and thus provide an indirect means of dating groundwater. This is especially true in the northern states where larger shifts occurred than in the Southern states.

Sulfur Isotopes

Isotopic ratios of $^{34}\text{S}/^{32}\text{S}$ from sulfate dissolved in the water can give indications on the origin of the sulfur and thus trace the subsurface history of a water mass, because sedimentary sulfate, marine sulfate or igneous-metamorphic sulfur are isotopically very different. Unfortunately, large isotope fractionations occur between oxidized and reduced sulfur species, and both inorganic as well as biologic processes can have a profound impact on the distribution of the various species. If sulfur isotopes are used, it is therefore essential to get some information about the Redox-potential of the

system, or, better, isotope and quantitative chemical analyses of both oxidized and reduced sulfur species. Mass balance considerations are then used to discern the origin of the sulfur in the water.

RECOMMENDATIONS

A number of recommendations about procedures and research and equipment needs are implicit in the above discussions on the various available techniques.

In summary, they are

1. Engineering equipment needs
 - a. Refinement of clean drilling methods such as reverse air technique
 - b. Development of small-diameter, positive displacement deep well pumps
2. Studies to increase knowledge of geochemical processes affecting waste transport
 - a. Field measurements of dispersivity and distribution coefficients of many chemical and isotopic species in different geologic terrains.
 - b. Comparative studies in mines and equivalent geologic terrains using borehole data to discern the effects of stress (e.g., the mine itself) on the regional geochemistry.
 - c. Studies of U-disequilibrium methods in well-characterized groundwater systems to learn the principles of uranium geochemical behavior so its usefulness as a groundwater dating method can be evaluated.
3. Considerations in site evaluation program planning.
 - a. Geochemical sampling needs should be integrated with drilling method design and the hydraulic testing scheme adapted.
 - b. Assurance of reliable analytical facilities.

TASK 6: MONITORING PROGRAMS TO VERIFY FLOW SYSTEMS

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BACKGROUND

With few precedents set by other monitoring systems, such as those designed for nuclear events, the working group has produced an innovative tentative plan. A comprehensive program may be built upon this, to serve the usual requirements for safeguarding high-level radioactive waste stored in non-salt rock repositories, especially crystalline rock masses whose major defects are fluid-bearing fractures. The monitoring system has the objectives of confirming design assumptions relating to the integrity of the containment medium, and to detect any changes of rock properties or contaminant transport over a span of at least 100 years; parts of the system may operate much longer.

Because both exploration and monitoring-system drill holes may destroy the natural integrity of the medium, and both may perturb such conditions as the ambient hydraulic, thermal or chemical fields, the exploration and monitoring facilities should be conceived concurrently. Economy will also be effected thereby, since all holes may serve multiple purposes. Because monitoring is to provide vital forewarnings of containment compromise and design and prediction failure, abundant data redundancy is well justified. Back-up systems need to be installed to make the monitoring fail-safe during the long interval of recoverable storage so as to provide a reliable basis for deciding to embark on the permanent waste disposal phase. Insofar as possible, we should avoid reliance on models of behavior to relate transport to indirect parameters. For example, fluid velocity in critical conduits

needs to be measured instead of placing reliance on permeability, porosity and hydraulic gradient measures.

It is considered vital to retain the natural integrity of the rock lying between the repository caverns and the biosphere, avoiding any perforations that cannot be guaranteed to remain safely sealed. Any exceptions would be contingent upon research to establish adequate borehole plugging methods. Thus the work of locating and exploring the site should be done in places remote from the ultimate emplacement or by non-destructive methods, and the openings necessary for detailed exploration, for construction and installation of monitoring devices may conceivably be done from one or more galleries below the storage level, whose access is by a remote shaft. An economy in drillhole lengths can also be effected thereby if the storage depth is significant (1-2 km). Of course, the feasibility of sublevel galleries would have to be studied before choosing this method of access to instrumentation.

Monitoring spans the entire chronology of storage development and operation: baseline data-gathering needs to precede any site disturbance and to accelerate during site exploration and construction. Its critical employment will be to predict and detect contaminant escape during the short-term storage period (10 to 100 years). When the facility is deemed safe for permanent disposal, monitoring systems to verify that the changes occurring during closure (such as restoration of pre-exploration piezometry) do not alter the security of the containment for long term (100 - 10,000 years?) storage.

STATE-OF-THE-ART

Parameters that can currently be monitored include fluid pressure, stress, deformation, temperature, fluid salinity, and the radioactive character of both rock and contained fluids. Whether a direct measurement of flow is possible in the largely impermeable test environment needs investigation.

Whereas many of the instruments for the tasks are commercially available, some of them will be called upon for emplacement at untested depths, pressures and temperatures. Laboratory testing will be required to confirm their long-term operability, and extensive development work will be needed to design new devices or to adapt existing ones to the unusual conditions that are anticipated.

For instance, transducers for non-displacement fluid pressure measurement appropriate to conditions of very low permeability are available now, but their prolonged usefulness at temperatures approaching 200°C near the storage vault is not now assured. Measurement of stress changes with solid inclusion devices or other types is currently feasible, but in applications of 100-year duration, the electrical insulation and corrosion effects will probably require evaluation and modification.

Deformation measurement for monitoring cavern closure can be accomplished with existing extensometers spanning the repository. Adaptation to the severe thermal regime and remote registration will require development work. Accessibility provided by a system of sub-level monitoring galleries would facilitate operations.

Thermal monitoring will play an important role in analysis of containment, because the heat conductivity is strongly dependent upon fluid convection and the functioning of the containment structure will depend heavily on thermal limitations established during design. No obstacle to the use of conventional thermistors is currently envisioned for the entire range of expected temperatures.

A promising class of monitoring devices can be designed around simple resistance cells to detect salinity changes. Fluid movement can thereby be detected if electrolytes or soluble salts are emplaced in critical locations up-gradient of detection devices. Perhaps waste containers could be coated

to release salts that would be precursors to escaping contaminants. Development of such chemical tracer systems is in order.

Radioactive monitoring, built upon the current advanced technology, can clearly play a vital role in detecting fluid movement. With careful characterization of the background radiation and its sources, a program, with appropriate in-situ devices to register a variety of emissions, can be designed to detect escaping products of decomposition of the waste, the waste itself, and most importantly, radioactive precursor tags placed in the rock around the cavern, in the backfill material and on the waste containers. Monitoring needs to be extended to all man-made perforations of the containment rock body.

RECOMMENDATIONS

It is recommended that alternative monitoring systems be conceived and studied to assure performance of the repository as designed, both in the near-field where the effects of the structure can presumably be predicted and in the far-field, remote from the region of perturbation. The latter should utilize any and perhaps all pre-existing openings, such as mines and wells. The monitoring program will vary in scope during the several definable time periods.

Baseline Monitoring (0-1 year)

The hydraulic potential field will doubtless be highly significant in site selection, exploration, analysis of response to disturbance, and in prediction of transport. Thus, the early characterization and subsequent changes require thorough data collection via fluid-pressure transducers and piezometer nests (i.e., multiple installations in single holes). Baseline monitoring should long precede any other site disturbance, so that any

transients initiated by monitor holes may decay sufficiently to characterize the potentiometric background. The hydraulic region of interest may extend well beyond the facility protection area, and include any adjacent aquifers.

The hydrogeology must be well understood before an effective monitoring system can be emplaced for background characterization. Topographic and geologic basins (groundwater flow system) are subject to water balance studies, updated by meteorologic and land-use changes. Water-table monitoring in shallow slim wells should be conducted concurrent with deep piezometric monitoring. Attempts to measure fluid-flow directly should be made before site disturbance is produced. These may include cross-site tracer techniques, and if adequate tools can be developed, direct velocity measurements in fractures should be undertaken.

The existing temperature field must be defined by borehole thermistry in peripheral observation wells under both hills and valleys, so that the subsequent problem of coupled transport of heat and fluid may be analyzed fully. The in-situ stress field needs to be determined before perturbation, utilizing a variety of techniques, such as hydrofracing, against which permanent implantation devices can be calibrated. Radiation levels in observation holes are necessary to permit interpretation of future changes.

Conditions affecting work safety may include, in part, the following:

- a. Ambient radiation levels, above and below ground (e.g. mines)
- b. Air quality, soil gases and dissolved gases
- c. Meteorology
- d. Biologic inventory
- e. Teleseismicity and microseismicity
- f. Geodesic measurements (level lines, tiltmeters, geodimeter network)

Construction-Phase Monitoring (1-10 years)

All of the systems deployed for background determination should be observed periodically, and additional devices should be installed in near-field locations disposed essentially radial to the storage facility. If the site is chosen with a natural horizontal groundwater gradient, vertical exploration holes need not perturb the piezometry.

Near-field installations, as could be drilled from a sub-level gallery system, should monitor the following:

- a. Hydraulic potential changes resulting from excavations.
- b. Fluid flow in discrete fractures as drainage proceeds.
- c. Stress changes and fracture closure as excavation perturbs the stress field.
- d. Rock noises, to register the locations of new defects and subsequent rock failures.
- e. Ambient radiation.

For the subsequent use, the following should be employed:

- f. Thermistors to record the thermal transient
- g. Gas-phase detectors to record escaping entrapped air or radiogenic gases.
- h. Benchmarks for precise surveying, determination of convergence or thermal deformation.

Short-Term Monitoring (10-100 years)

If the monitoring system is kept accessible for an extended period, as may be possible with a sub-level gallery configuration, the devices can be observed, serviced or replaced. Pore-pressure control or flow modification remains possible by grouting or draining the peripheral rock during the critical thermal transient period when crack propagation is most likely. If desirable, the monitoring gallery can be pressurized by flooding, so that rock behavior

under increasing fluid-pressure conditions can be monitored remotely well in advance of a commitment to non-recoverable disposal.

All installed near and far-field monitoring systems enumerated above should be maintained and observed during this extended period, but it is expected that experience will dictate changes.

Long-Term Monitoring (100-10,000 years?)

Monitoring devices accessed by electrical conduits in the remote shaft and monitoring gallery system will eventually become inoperable. Surface-access devices, mostly remote installations deployed during the base-line phase, may be replaced periodically to permit perpetual surveillance over the repository. These will be necessary to assure that no major breakdowns of containment security take place. In addition, a periodic re-evaluation of the following is in order:

- a. Topographic changes that could expose the repository or alter the groundwater regime.
- b. Hydrologic changes, such as infiltration or drainage changes.
- c. Tectonic changes, including seismic effects, changes in stress, geodesy.
- d. Water chemistry and radiation measurements in observations holes, mines and streams should be continued to detect precursors. Sealed vertical holes and shafts are especially sensitive.
- e. The physical security and isolation of the protection area.

In addition to the above recommended monitoring program, there is need for research and development on devices and systems to do the following:

- a. Measure directly the flow of fluids in fractures.
- b. Measure the deformation of individual fractures upon change of effective stress.
- c. Insure the prolonged reliable remote registration of any electric devices.

- d. Evaluate and modify existing devices for anticipated temperature ranges.
- e. Detect gas evolution and its transport in fractures.
- f. Investigate radiation damage to monitoring devices and conduits.
- g. Design chemical and isotopic monitoring schemes to detect intentional precursors as well as waste escape.

APPENDIX

List of Attendees
Seminar on "MOVEMENT OF FLUIDS IN LARGELY IMPERMEABLE ROCKS"

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