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GEOTECHNICAL ASSESSMENT AND INSTRUMENTATION NEEDS FOR NUCLEAR WASTE ISOLATION IN CRYSTALLINE AND ARGILLACEOUS ROCKS

SYMPOSIUM PROCEEDINGS

July 16-20, 1978

For Reference

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Earth Sciences Division
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Berkeley, California 94720

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Prepared for the U.S. Department of Energy under Contract No. W-7405-ENG-48

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GEOTECHNICAL ASSESSMENT AND INSTRUMENTATION NEEDS FOR NUCLEAR WASTE ISOLATION IN CRYSTALLINE AND ARGILLACEOUS ROCK

SYMPOSIUM PROCEEDINGS

July 16-20, 1978

Arranged By

LAWRENCE BERKELEY LABORATORY
EARTH SCIENCES DIVISION
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BERKELEY, CALIFORNIA 94720

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GEOTECHNICAL ASSESSMENT AND INSTRUMENTATION NEEDS FOR NUCLEAR WASTE ISOLATION IN CRYSTALLINE AND ARGILLACEOUS ROCK

SYMPOSIUM PROCEEDINGS

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SUMMARY

SUMMARY

Today there exists in the United States a large volume of nuclear wastes that result from both military and commercial activities. The United States has to date placed major emphasis on disposal in only one rock type--salt--whereas other nations have considered other rock types, such as granite in England and Sweden and clays in Belgium. No comprehensive evaluation of isolation in rocks other than salt has been made in the United States, and it is most appropriate that other rock types be evaluated both for constructing disposal sites in areas devoid of salt and also for having alternative waste management plans in case substantial problems are encountered in using salt as a disposal medium.

To evaluate the state-of-the-art, research needs, and research priorities related to waste disposal in largely-impermeable rocks, scientists and engineers working on geologic aspects of nuclear waste disposal were brought together. The Geotechnical Assessment and Instrumentation Needs (GAIN) Symposium for Nuclear Waste Isolation in Crystalline and Argillaceous Rocks was held July 16-20, 1978 in Berkeley. This report and recommendations are the proceedings from that symposium.

The location, design, and testing of a potential nuclear waste disposal site are both a geologic and an engineering problem. Disposal requires isolating the wastes from the surface and subsurface of the earth for a period of time of ten to hundreds of thousands of years. Engineers have never before been called upon to predict the behavior of structures or the flow of groundwater so far into the future.

Although geologists deal with large time spans in an historical context, they rarely need to make quantitative long-term predictions of future geologic events. Thus the symposium participants addressed the most significant problems of radioactive waste disposal: Are measurement techniques adequate to acquire the necessary geologic and engineering knowledge once a site is chosen? Are measurements and theory adequate to describe the system as it presently exists? And is theory well enough developed to allow prediction of future depository behavior with reasonable assurance?

Problems of waste isolation depend upon knowing the properties of crystalline and argillaceous rocks, the movement of interstitial water if it exists in fractures in largely-impermeable rocks, the geochemistry of groundwater and, ultimately, interactions of waste with the surrounding rock. The symposium participants consequently grouped themselves into three interdependent panels: Rock Properties, Fracture Hydrology, and Geochemistry.

All panels agreed that Full-Scale Test Facilities should be established immediately in order to aid engineers and geoscientists in obtaining experience with every aspect of disposal problems in crystalline and argillaceous rocks. Only within the past few years has attention been given to fluids in largely-impermeable rocks; hence the body of knowledge and experience generated to date is relatively small. Before confidence can be given to predictions regarding waste disposal in such rock masses, much more experience under field conditions is necessary. The most rapid way to promote generation of incisive experience is to establish Full Scale Test

Facilities. The international scientific and engineering communities would be invited and encouraged to perform tests and experiments in the same rock masses. Test Facilities should therefore be established as soon as possible in several rock types and geologically different environments.

The Rock Properties panel recommends expanded research and development to maximize the ability to collect data from small-diameter (76 mm) boreholes -- drilling techniques and fluids should be optimized to decrease disturbance and contamination; slim-hole tools should be developed to retain moisture conditions and pore pressure in cores; surface preparation tools should be evaluated and improved, if necessary, so that the quality of observation of the walls of the borehole is enhanced; and continued development of procedures for retrieving core is necessary so that joint apertures and other properties can be measured in the laboratory. There is need for development of a suite of slim-hole logging tools, particularly with regard to detecting fractures and evaluating their apertures, frequencies, and orientations. Additionally, since there is a general lack of experience in well log interpretation in crystalline rock, logging tools must be field calibrated and tested in these and the other rock types that may be considered for a repository.

The in situ state of stress is of central importance to disposal siting because stress affects not only the mechanical stability of the repository, but it also affects the potential for deformation, seismic activity, and permeability changes along existing and new fractures. Overcoring and hydraulic fracturing are used to evaluate stress, with the latter the only technique presently used for significant

depths in boreholes. It is thus recommended that research be conducted on borehole stress measurements, including methods of determining stress from a borehole that would be representative of a large mass of rock, development of down-hole tools for stress determinations at depths of 500 meters or greater and that have stabilities on the order of a decade, and studying accuracy of the various methods of stress-determination by working with large rock masses (e.g., 1 m cubes) under triaxial stress in the laboratory.

Both the Rock Properties and the Fracture Hydrology panels strongly recommended full-scale heating experiments in addition to the very few that have been and will definitely be implemented. Full-scale experiments in a number of rock types are needed for fundamental data-gathering, testing of correlations and theories, and model construction and validation. Full-scale experiments recommended by the Rock Properties panel would examine thermally-induced deformation and cracking and changes in permeability, sonic velocity, thermal cracking, and electrical conductivity.

Modeling was discussed by all panels. It was generally agreed that there exist techniques to construct models. However, what is lacking is the fundamental engineering and scientific knowledge to be incorporated into the models and to validate those models under varied conditions. Individual models already available can handle separately fluid flow, heat transfer, mechanical behavior, and chemical reactions, but many of these have not been adequately validated. Higher-order models include effects of coupling between two or more of the above categories; several of these coupled models are available

and are being constructed. Various work can be done to test the accuracy of these models as well as to verify whether adequate physics and chemistry have been incorporated to describe a given field situation. However, it was a consensus that validation of models will remain in doubt until large-scale experiments at least on the order of five years have been conducted and compared with simulation results. Until these are performed, it is uncertain how much additional work will be necessary to validate predictions of behavior in the far future.

The Fracture Hydrology panel recommends a significant research effort to improve determination of fracture permeability in a rock mass, especially regarding directional permeability, the hydraulic continuity of fractures, and the effect of stresses (thermal, tectonic, lithostatic, and shear) on aperture and permeability. Only recently has consideration been given to the problem of in situ measurements of permeability of fractures in largely-impermeable rocks. Laboratory and field tests are currently underway to determine fracture permeability by introducing a pressure transient in a borehole, and one test is in progress to assay permeability measurement in a mine opening by monitoring changes in humidity of ventilation air.

Determination of directional permeability is also in an initial stage of testing, and potential techniques require further theoretical and instrumental development. Determining the effect of stresses on fracture apertures and permeability is both a laboratory and field problem, and was also an area of research recommended by the Rock Properties panel. Determining the hydraulic continuity of fractures is a problem that needs incisive, fundamental work.

Of particular importance in extrapolating laboratory data to field conditions is the assurance that the laboratory sample corresponds to a representative elementary volume (REV) for a given field. When examining fractured rocks, the REV may be larger than current testing machines can handle, as appeared to be indicated in a recent experiment. Both conceptual models and experimental investigations are needed to allow confident extrapolation of laboratory data on fracture permeability to field occurrences.

Fracture volume, size distribution, and interconnection are important variables in estimating fluid velocity for travel-time computations and in estimating the void surface area available for geochemical reactions. The panel concluded that no effective means now exists for directly measuring these properties, particularly in situ. Theoretical and experimental work should be encouraged, but the problem should also be approached by means of field tests employing tracers and radionuclides. Such field tests, which would be partially site-specific until enough was learned to generalize, were recommended by both the Fracture Hydrology and Geochemistry panels.

Geochemistry is of importance in investigating the groundwater flow regime at potential depository sites and in the multiple barrier concept; in synthesizing the most refractory form of waste material, in recommending the most effective plugging and backfill materials, and in determining the results of chemical reactions between waste materials and the groundwater/rock system.

Much discussion in the Geochemistry panel centered about the rock barrier -- elucidating the flow regime, sorption of waste products on fractured surfaces, and considering potential mechanisms such as colloid formation and organic complexing that might reduce or enhance the rock's effectiveness as a natural barrier. Geochemical reactions may slow radionuclide migration with respect to water flow and diffusion; if so, this extra safety factor should be known and incorporated into models.

Sorption of waste products by rock surfaces is only now being investigated. Continued intensive work is needed in this area, and it is important that laboratory studies be designed so that their results will be useful in rigorous thermodynamic calculations. Kinetic factors in sorption should also be noted so that complete models can be constructed.

There is a general lack of information on the behavior of actinide aqueous and solid species that are important in dissolution of waste forms and in groundwater transport processes; there is also a dearth of information on the potential for actinides to form colloids in groundwater. Recent work suggests that actinide, form complexes with organic materials occurring naturally in groundwater may be important, that this topic needs much further investigation. All of these fundamental topics are recommended for early attention. Once this body of thermo-mechanical and kinetic data becomes available, it will be incorporated into models and results compared with field radionuclide and tracer tests to provide model validation.

Major instrumentation needs involve development of techniques for measuring dissolved aluminum, better contamination-free drilling and sampling methods, and development of stable and long-lived borehole electrochemical sensors. It was also recommended that an additional groundwater dating technique be developed to confirm ^{14}C dating.

This summary has placed emphasis on the more important research and instrumentation recommendations made by the symposium participants. The following text gives state-of-the-art reviews, amplifications and justification for research recommendations, additional topics considered, and lower-priority research and instrumentation recommendations.

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INTRODUCTION

INTRODUCTION

The need to address clearly and comprehensively the nuclear waste management issue is critical. For more than three decades, military and commercial nuclear wastes have been generated in increasing amounts. Yet, presently a consensus has not been reached on methods of nuclear waste containment, storage or disposal.

In order to support a comprehensive research plan for nuclear waste isolation, the Department of Energy (DOE) asked Lawrence Berkeley Laboratory to begin a nuclear waste research needs program. The program initiated a study to define the state-of-the-art, to assess the utility of crystalline and argillaceous rock and to identify research and instrumentation needs for nuclear waste isolation.

The Geotechnical Assessment and Instrumentation Needs Symposium (GAIN) represents a major effort to address comprehensively the nuclear waste disposal issues from a spectrum of multi-disciplinary perspectives. A systems approach was used to integrate the technical and engineering disciplines and their interdependency with the constraints and interactive character of nuclear waste disposal. A matrix (Figure 1) illustrates the inter-dependency of the technical parameters and nuclear waste isolation.

The GAIN Symposium proceedings is a statement of the present knowledge and research needs for isolating nuclear wastes in crystalline and argillaceous rock. It is a report based on the expertise and recommendations of seventy internationally-recognized scientists and engineers, gathered at the symposium in July 1978. The report contains brief statements by DOE on National Terminal Waste Storage Program, and the

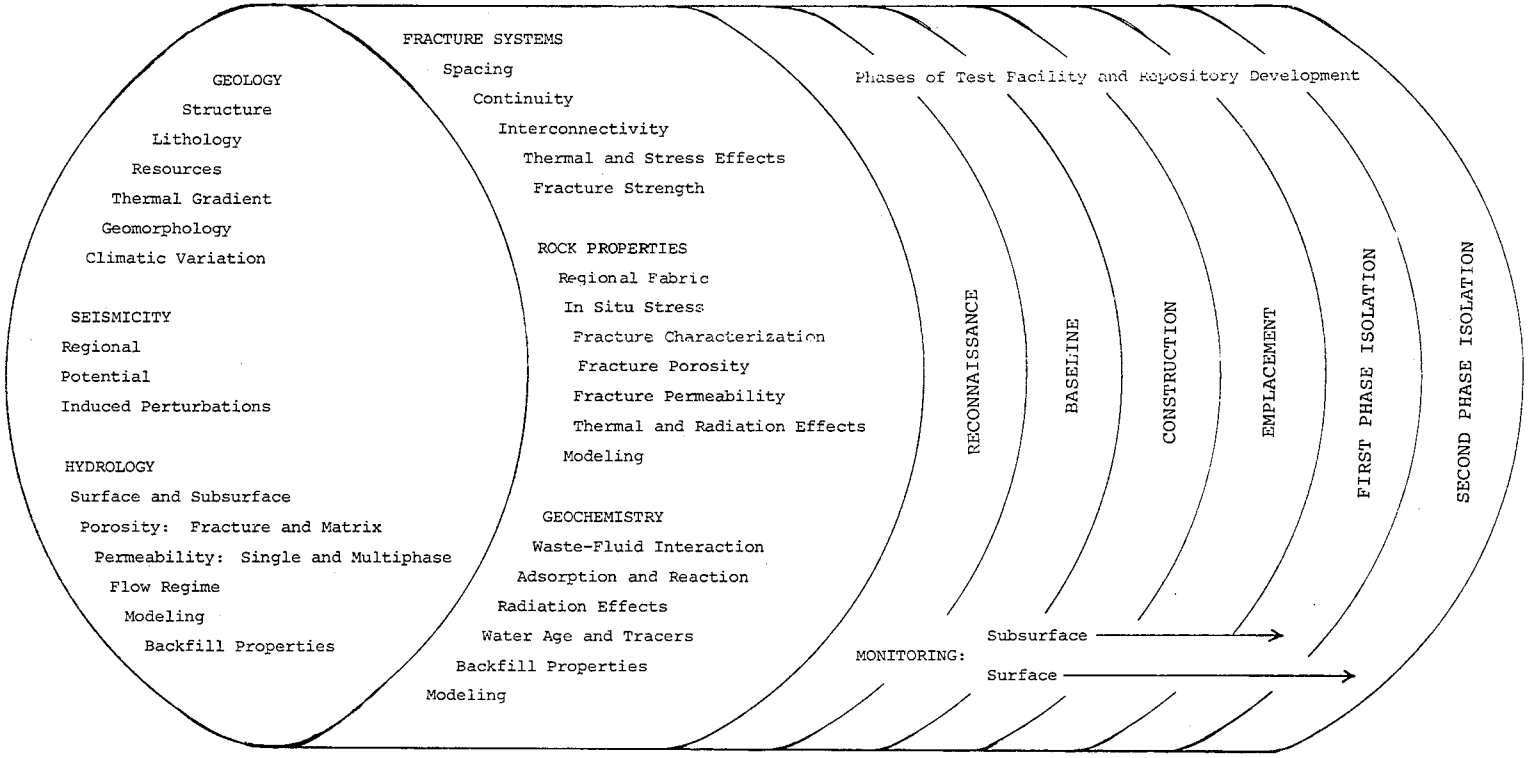

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Fig. 1. Geotechnical parameter matrix for full-scale test facility and repository development.

U.S. Nuclear Regulatory Commission on Guidance for Judging Site Suitability, papers on the technical sessions, and bibliographies listing referenced literature, the Swedish KBS reports and United Kingdom AERE reports.

The report is structured around three geotechnical perspectives on isolation of nuclear waste. The Rock Properties panel focused on the physical characteristics of rocks, their discontinuities and in situ measurement of rock behavior. The Fracture Hydrology panel discussed directional fluid flow and permeability, development of comprehensive test facilities, modeling, and the hydrologic aspects of borehole analysis and shaft sealing. A third working group, Geochemistry, outlined nuclear waste containment and barriers, radionuclide transport and sorption, dating and tracing of groundwater, and waste-rock-water system geochemistry.

1. OBJECTIVES OF THE SYMPOSIUM

The GAIN Symposium took an integrated and interactive approach to research needs for nuclear waste isolation or disposal in crystalline and argillaceous rock. It offered a forum for analysis of nuclear waste issues from a broad range of scientific and engineering perspectives. The objectives of the GAIN Symposium were:

- to establish the state-of-the-art in nuclear waste isolation in crystalline and argillaceous rock;
- to determine the factors to be considered in assessing waste-rock interactions;
- to define the additional research that is needed before enough is known to evaluate each of these factors adequately;
- to establish the particular research and development issues or projects that are of the highest priority;

- to determine the instrumentation needs to measure the factors for site-selection and development; and to establish priorities in developing the needed instrumentation.

2. BACKGROUND AND CONTEXT OF GAIN

In view of the extensive research in the United States associated with disposal in salt, it is now necessary that assessment of other rock types be accelerated. In recent years, granitic rocks, basalt and shale have been considered (Schneider and Platt, 1974; Yardley and Goldich, 1975). Several European governments have initiated studies in crystalline and argillaceous rock units (International Symposium on Management of Waste from the LWR Fuel Cycle, 1976). The Report to the American Physical Society on Nuclear Fuel Cycle and Waste Management (1978) emphasizes the need to evaluate both salt and non-salt rocks for waste disposal. The report states, "We conclude that at least one demonstration facility should be developed in a medium other than salt, preferably granite, and thoroughly evaluated before the decision is made to develop a facility into a full repository" (APS, 1978, p. S108). It continues "...only modest design changes [from a salt repository] would be required to allow for different thermal and mechanical properties [of crystalline and argillaceous formations]" (APS, 1978, p. S71). The Interagency Review Group Report confirms the need to investigate more than one rock type. It states, "Detailed studies of specific, potential repository sites in different geologic environments should begin immediately" (IRG, 1978, p. 26).

3. DOE'S NATIONAL WASTE TERMINAL STORAGE PROGRAM

The U.S. Department of Energy has developed a program for National Waste Terminal Storage, the objective of which is to provide facilities for the permanent isolation of commercial radioactive wastes for which the federal government is responsible. This program includes:

- technology
- development
- design, licensing, construction and operation of commercial geologic repositories in salt and other geologic media, and spent fuel packaging facilities
- coordination of geologic repository projects for commercial and defense wastes and of alternate disposal methods

Presently the National Waste Terminal Storage program goals focus on developing a repository in salt with site selection in FY'80 and operation scheduled for FY'88 for retrievable storage and/or disposal of spent fuel or fuel reprocess waste. In addition, the program goals include evaluating basalt, granite, or shale for potential waste repositories and to develop the technology required for site selection, design, licensing, operation and decommissioning.

4. NRC REGULATORY GUIDANCE FOR JUDGING SITE SUITABILITY

Along with the DOE National Waste Terminal Storage program, the U. S. Nuclear Regulatory Commission (NRC) is currently developing its policy regarding repository site suitability. The points mentioned below should be regarded as tentative criteria which the NRC will use to judge site suitability.

In the view of the NRC, the repository must be analyzed and evaluated as a system. This system includes not only the subsurface excavations made for the emplacement of waste but all of the hydrologic and geologic

elements of the surrounding region which may influence the effectiveness of the repository. Additionally, social, economic and political constraints will enter into site-suitability decisions. Such constraints are presently less well-defined than the principally technical considerations cited below.

The ultimate objective of placing waste in a deep geologic repository is to isolate it from the biosphere for a sufficiently long period of time that whatever radionuclides which may eventually reach the biosphere have decayed to or been diluted to innocuous and therefore acceptable levels. At the present time, the NRC is tentatively considering that radiologic performance objectives for a repository will define annual dose or dose commitment limits; and those limits will be in accordance with standards developed by the Environmental Protection Agency (EPA).

The tentative criteria and considerations developed by NRC to be used to judge site suitability are:

A. The presence of a system of multiple naturally occurring barriers to waste migration.

B. Evaluation of this system will be based on considerations of

   1. the hydrogeologic system
   2. geochemical interactions between waste, packaging, emplacement medium and groundwater
   3. the thermal and radiologic effects of the waste on the host rock
   4. the tectonic and seismic stability of the site
   5. the effects of unplanned intrusions either by man or natural events

6. the potentially deleterious effects of exploration, construction and decommissioning
7. depth of emplacement
8. thickness and lateral extent of the emplacement medium
9. the effect of uncertainties associated with the parameters required to evaluate the site.

C. The present and anticipated future values of the hydraulic parameters shall be such that the migration of waste from the repository to the point of entry to the biosphere shall not result in concentrations of radioactivity which exceed the levels stated above.

D. Testing and exploration techniques shall have been such that their potential adverse effects on the long-term ability of the repository to isolate the waste will be minimized to the extent reasonably achievable.

E. Determinations of site suitability shall consider the results of geological, hydrological and climatological investigations extending to a distance sufficient to provide adequate understanding of the factors operating in the vicinity of the repository including potential long-term variations in the hydrogeological regime.

F. The actual or potential resource value of the repository site shall not deprive society of necessary and valuable resources or invite further exploration or development to the extent reasonably achievable.

G. Long term-surveillance and administrative controls shall not be prerequisite to assuring the protection of the public health and safety or the preservation of environmental quality.

5. ROCK CHARACTERISTICS

Crystalline and/or argillaceous rock may have the characteristics necessary for safe, economical, and environmentally feasible repository. These rock types have been given high priority in Canadian, Swedish, French, Belgium and Japanese waste disposal research. For comparative purposes, salient properties of each rock type are reviewed in Table 1. Specifically, permeability, solubility, rock strength, regional stability, and thermal properties are significant characteristics for nuclear waste storage disposal and repository siting. Table 1 indicates that all rock types have potentially favorable and unfavorable characteristics. Crystalline and argillaceous rocks need to be considered because they overcome some of the limitations of salt as a repository medium and have additional favorable characteristics of their own.

Crystalline rocks are widely distributed throughout the United States (Figure 2) and include granite and other igneous and metamorphic rocks. They are basically almost impermeable and are homogeneous and have relatively high compressive strength. Interstitial permeability is exceedingly low. What seepage exists results from flow along fracture or joint planes in the rock mass. Site studies conducted by Wenner (1976) found some Canadian mines to be virtually dry below 1,000 metres, thus indicating that nuclear waste may possibly be isolated from groundwater in crystalline rock at greater depths. However, seepage may still occur and one needs to know the ventilation system in order to assess if interstitial water is being removed by vaporization. Crystalline rocks can be mined to great depths due to rock strengths and tend to be homogeneous and isotropic over large vertical and lateral distances.

Table 1. Implications of some rock properties for deep burial of wastes by rock type.

Characteristic	Impact	Crystalline	Argillaceous	Salt
Thermal Conductivity	allowable power density of waste	high to low 0	low -	high +
Permeability	radioactive nuclide transport velocity	high to very low, through fractures 0	high to very low, through fractures 0	very low +
Solubility	long-term stability	low +	low +	high -
Strength	mine stability	high +	low -	low -
Plasticity	mine stability "self-sealing" quality	low + -	high - +	high - +
Ion-exchange	ability to absorb radio-nuclides	usually none -	high +	none -
Density	long-term gravitational stability when deeply buried	usually high +	low to high 0	low -
Volatile Content	shattering on heating, radiolytic gas formation	low +	high -	low to high 0
Generalized Geologic Environment of large continuous bodies		in continental shields, mountain ranges, volc. plateaus	in sedimentary basins	in sedimentary basins
	unfavorable association with gas, oil, water-bearing beds	+	-	-
	proximity to seismic zones	0	+	+
Generalized distribution in U.S. of large continuous bodies	availability in arid zones & zones of low population density	West, North, East +	East, Central West 0	Central East -

Rating scale: + = favorable to waste storage
- = unfavorable to waste storage
0 = not clearly favorable or unfavorable
(because of intermediate value or wide range of values)

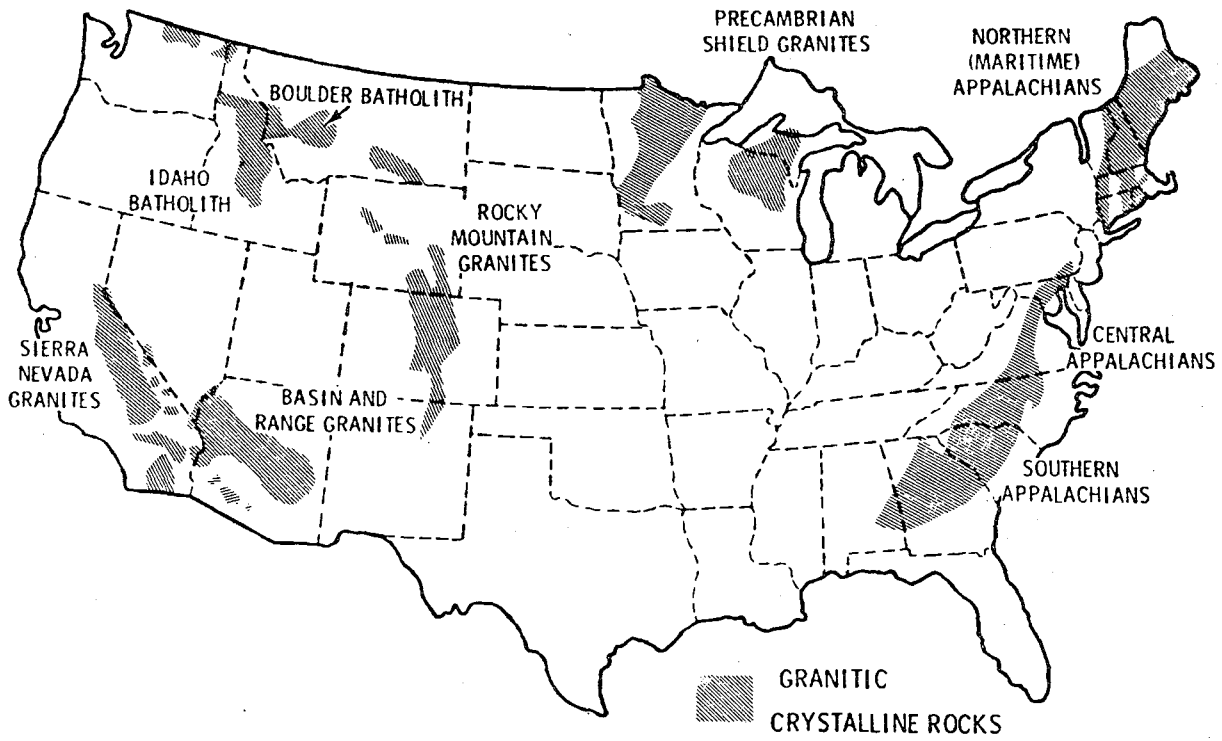

Fig. 2. Granitic rock in the contiguous United States.

These properties add to repository integrity and to modeling and prediction of rock mass behavior. Most crystalline rocks undergo little mineral alteration or volume change due to thermal effects considered in repository design (USGS, 1976).

Argillaceous rocks, including shale, claystone, argillite, and slate have several properties favorable for nuclear waste isolation. Their distribution within the United States is shown in Figure 3. Argillaceous rocks have high ion-exchange capacity, thus increasing their ability to adsorb radioactive nuclides and to retard nuclide migration. Some argillaceous rocks extending over broad geographic areas, such as claystone, have extremely low permeability. Many argillaceous rocks have high plasticity which is also a favorable characteristic and increases the "healing" of fractures.

In general, if demonstration facilities for repositories were developed in more than one rock type, it would allow substantial flexibility for waste management decisions in the future, as demonstration facilities reveal the actual performance of the different rock types (OWI, 1976, p. 7; APS, 1978, p. S138).

6. ACKNOWLEDGEMENTS

Primary acknowledgements are due to the imaginative and creative scientists and engineers who, over the past several years, have confronted the dilemma of nuclear waste isolation and shaped the ideas in nuclear waste research. More immediately, great appreciation is due to Dr. Thomas Lomenick, Oak Ridge National Laboratory and Dr. James Duguid of Office of Nuclear Waste Isolation for their assistance in providing overall guidance. We particularly would like to thank Mr. Lars Bertil

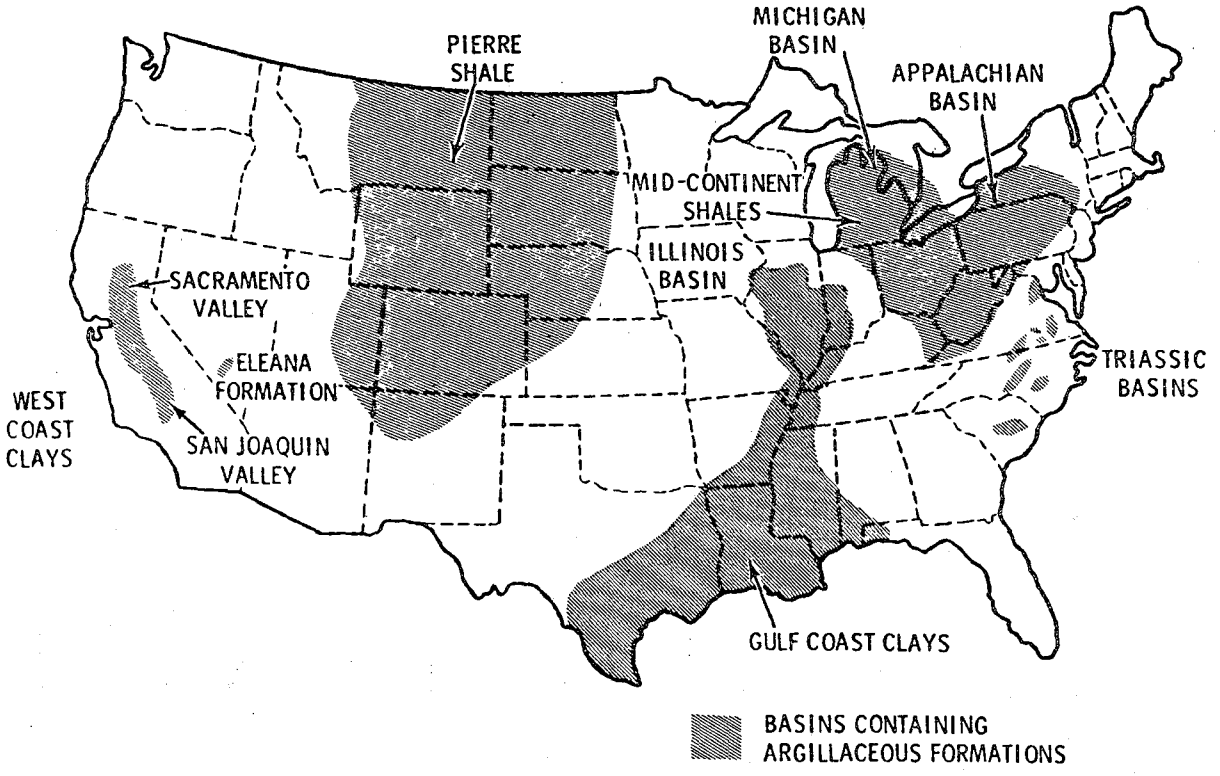

Fig. 3. Shale formations in the contiguous United States.

Nilsson and his colleagues in the Swedish Nuclear Fuel Safety Program for providing the bibliography of KBS technical reports which is in Appendix B. We would also like to thank Dr. Patrick Bourke of AERE Harwell for providing the bibliography of radioactive waste management in the United Kingdom which in Appendix C. Our gratitude is also extended to DOE for sponsorship of the symposium and to Lawrence Berkeley Laboratory staff and countless hands who made the symposium and this report a reality.

This report summarizes the technical discussions of the GAIN Symposium. It was prepared by the working panels and edited by the chairing committee and Lawrence Berkeley Laboratory. The views, opinions, and recommendations expressed in this document are those of several authors and it is inevitable that material is missed or omitted which others may consider important. The Chairing Committee would be pleased if readers would be kind enough to bring to the committee's attention ideas, recommendations or credits that they may consider significant and any of the errors which may have occurred in the course of editing and rewriting. It is hoped that the GAIN report will provide Office of Nuclear Waste Isolation and the Department of Energy a comprehensive review of the state-of-the-art and research needs in nuclear waste management.

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ROCK PROPERTIES

ROCK PROPERTIES

William Hustrulid, Reporter
Richard Thorpe, Secretary

Howard Pratt, Moderator
William Klauber, Secretary

Panelists

Working group #1: EVALUATION OF ROCK PROPERTIES FROM BOREHOLES AND BY REMOTE SENSING

Philip Nelson, Chairman
Bjorn Paulsson, Secretary

Donald Caldwell
Charles Fairhurst
Bernard Fuega
William Hustrulid
Pavel Kurfurst
Bronko Leskovar

Working group #2: EVALUATION OF ROCK PROPERTIES BY LABORATORY TESTING

Wolfgang Wawersik, Chairman
Richard Thorpe, Secretary

William Brace
Fred Donath
Peter Hackett
Hugh Heard
Hans Carlsson
Richard Robinson
William Savage

Working group #3: EVALUATION OF ROCK PROPERTIES BY FULL SCALE IN SITU TESTING

Howard Pratt, Chairman
William Klauber, Secretary

Eugene Binnall
Mark Board
Tin Chan
Neville Cook
Richard Goodman
David Hodgkinson
Earl Hoskins
William McClain
David Pentz
Christopher St. John
Ove Stephansson

Working group #4: EVALUATION OF INSTRUMENTATION CAPABILITIES AND NEEDS FOR ROCK PROPERTY DETERMINATION

Charles Fairhust, Chairman
William Klauber, Secretary
Richard Thorpe, Secretary

ROCK PROPERTIES

1. INTRODUCTION

1.1 Problem Statement

Today there exists in the United States the equivalent of about 10^4 tons of spent fuel from DOE and a lesser quantity from commercial operations. Spent fuel from commercial operations is, however, accumulating at the rate of a few thousand tons a year. Equating a ton of spent fuel to a canister, it follows that within the next decade some 20,000 canisters of radioactive wastes will require disposal. Adequate and reliable isolation of nuclear wastes demands that any repository must be designed with a degree of certainty equal to, or exceeding, that of the other engineering of the nuclear fuel cycle.

Our knowledge of subsurface media and the conditions to which they are subjected is vastly inferior to that of other engineering materials. To a large degree, this derives from the complex composition and structure of rocks, and the alterations to which they have been subjected over geologic history.

Expert and lay confidence in engineering ventures derives to a very great extent from the vast body of experience upon which they are based and the thorough testing of structures prior to commissioning. Although there is considerable experience concerning underground excavation, there are many unique aspects about an underground repository for nuclear wastes which lie outside this experience. These unique aspects include temperature loading of the excavations by radioactive decay of the wastes and the need to isolate these wastes from the biosphere for long periods of time. The latter requirement implies, also, that

the long term adequacy and reliability of a repository will have to be demonstrated by prediction models rather than by proof testing as is common in engineering. Good predictive models require a thorough understanding of all the phenomena involved and their interactions, and an adequate and reliable description of the conditions initially prevailing at the repository.

Turning specifically to the unknowns introduced by the thermal loading from emplacing radioactive waste canisters underground, to date only about thirty canister-years of experience has been gained in salt and less than two canister-years in hard rocks.

In view of (a) the uncertainty of our current knowledge of subsurface media, (b) the inherent variability of the subsurface, and (c) the risks of long term surface storage of these wastes, it is imperative that a well thought-out program of research be formulated and then initiated.

This report considers (a) the state-of-the-art, (b) research needs, and (c) research priorities regarding the collection of rock property data for assessing disposal in crystalline and argillaceous rocks. Particular attention has been addressed to the types of data needed, the time frame required for collection, how the data would be used in evaluating containment, and the tools required for data collection.

1.2 Approach to the Problem

The evaluation of a site as a future nuclear waste repository will be done in phases such as shown diagrammatically in figure 4. Based upon information collected at each phase, a decision is made whether to proceed to the next phase or to stop. Although the cost

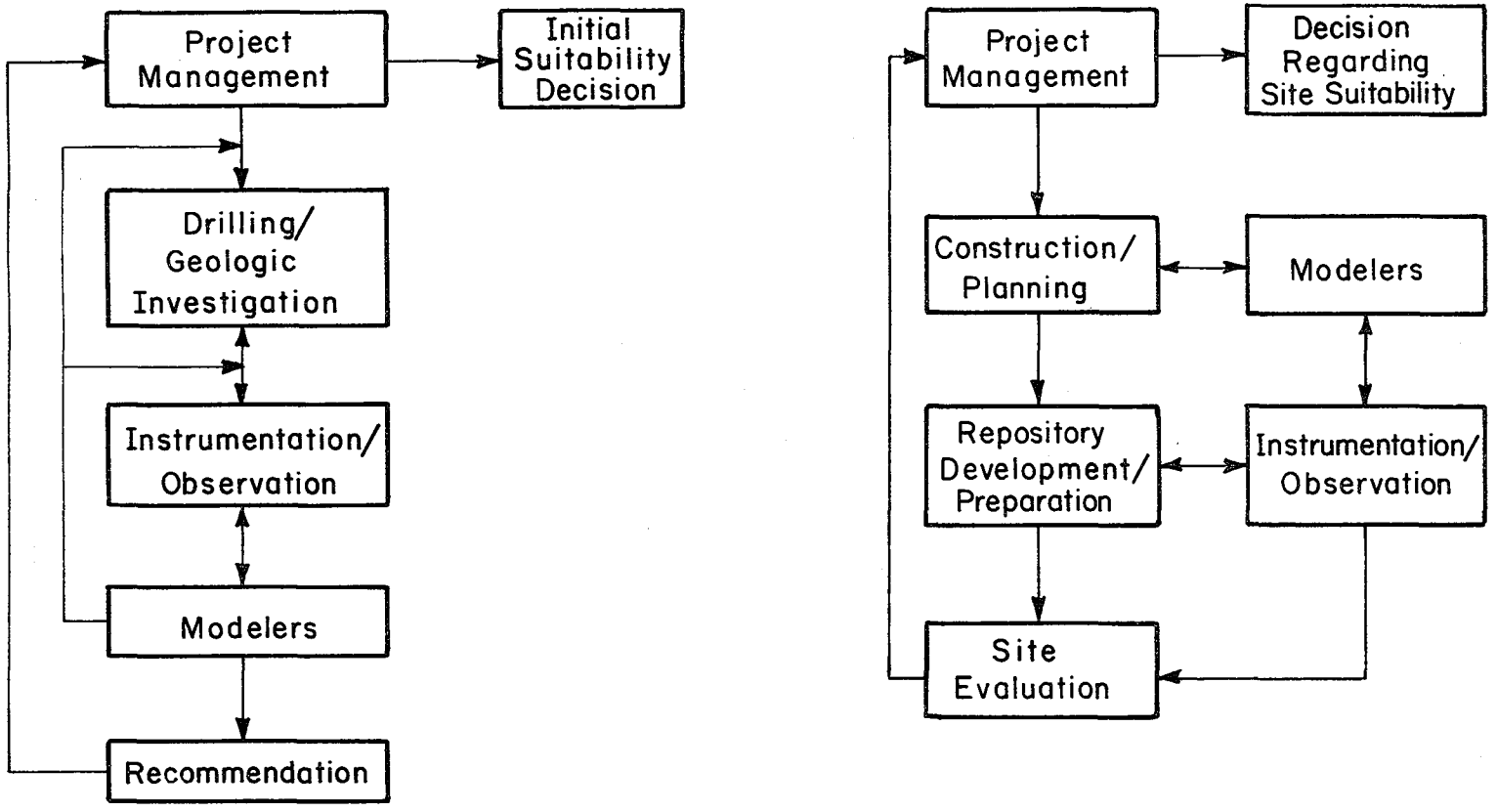

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Fig. 4. Time frame for data collection and instrumentation measurements.

Phase 1 -- Site evaluation
Objective: To find suitable site for waste repository.

Phase 2 -- Site construction
Objective: To construct the site with minimum disturbance to surrounding rock.

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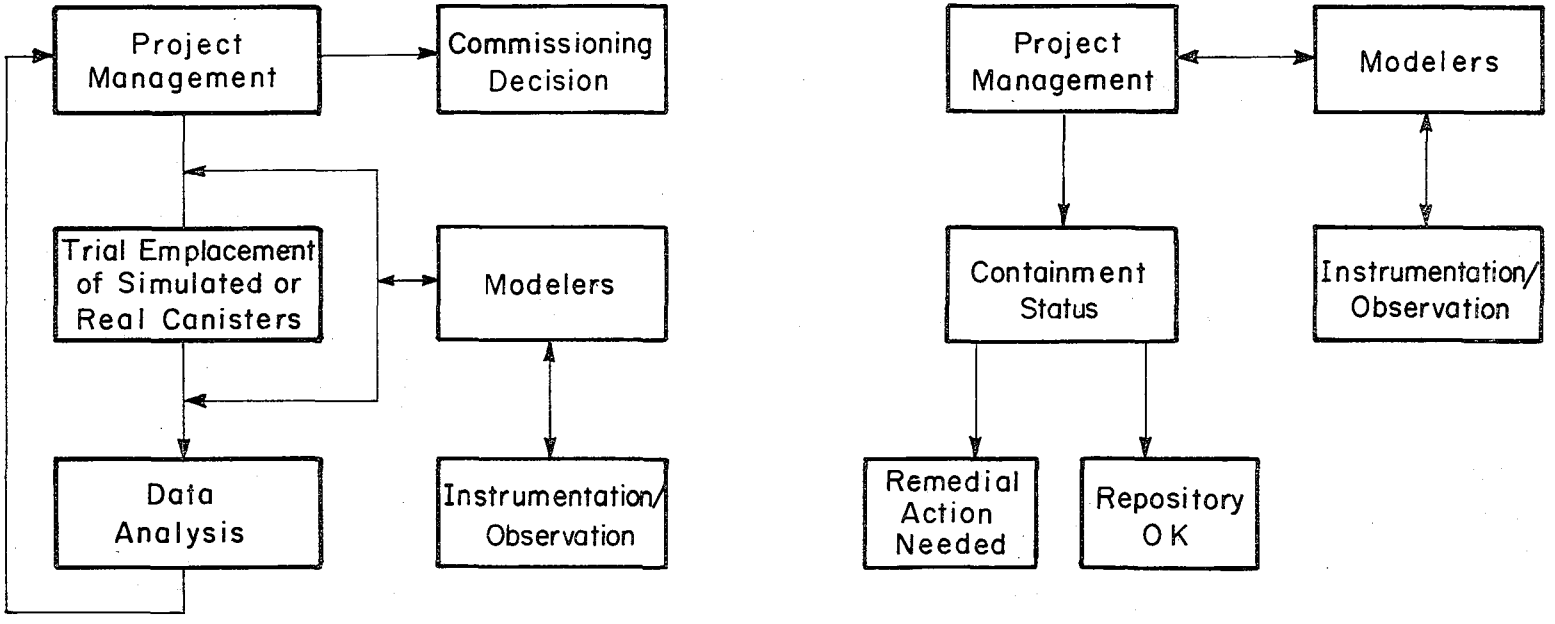

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Fig. 4. Time frame for data collection and instrumentation measurements (continued)

Phase 3 -- Pre-Commissioning trials
Objective: Determination of response of rock containment repository to simulate canister loading containment.

Phases 4 and 5 -- Post-Commisioning (near and long-term)
Objective: Evaluation of containment status of repository.

associated with each decision increases nearly exponentially from phase to phase, and the opportunity for collection of data upon which to make decisions increases. With a better understanding of the site one can decide (a) if the proposed design is adequate as planned; or if not, (b) what design changes are needed. In any evaluation process, it is imperative that as much good, relevant information as possible be collected and fully analyzed at the earliest possible date to minimize costly mistakes. This is particularly true with regard to underground nuclear waste storage sites in which the possibility of site rejection remains high in all phases. In the earliest possible phase one would like to:

a. Identify factors which would make a site unacceptable as a repository.

b. Identify unacceptable ranges of significant rock properties.

c. Develop techniques for identifying and measuring these rock properties. In this regard, one is not only concerned with "virgin" rock properties but also with changes in properties which would occur during (1) construction; (2) initial operation of the repository while retrievability is still feasible; and (3) long term disposal.

Modeling can be used with great advantage in selection of the most important parameters for study, experiment planning, data interpretation, and prediction. Because of its importance, a short discussion of the present state-of-the-art of geotechnical modelling is included together with remarks on research needs. As shown in figure 4, close working cooperation is required between

the experimentalists and the modellers. Accurate models and precise input are particularly important since the time over which observations can be made is many orders of magnitude less than the life of the repository.

To accomplish the stated objectives of the rock properties committee, the following four working groups were established:

Group # 1 - Evaluation of Rock Properties during Initial Site Investigations.

Group # 2 - Evaluation of Rock Properties by Laboratory Testing

Group # 3 - Evaluation of Rock Properties by Full Scale In Situ Testing

Group # 4 - Evaluation of Instrumentation Capabilities and Needs for Rock Property Determination.

It was felt to be more logical to organize working groups 1 through 3 on a rock property evaluation technique basis rather than on a time frame basis. To provide some guidance as to the correspondence between technique and time bases, the following table is provided:

Technique	Time	Role
Borehole/Remote Sensing	Phase 1	Major
	Phase 2-4	Supportive
	Phase 5	Major
Laboratory Properties	Phase 1-2	Major
	Phase 3-4	Supportive
	Phase 5	Lesser

Full Scale Testing	Phase 1	Lesser
	Phase 2-4	Major
	Phase 5	Supportive

2. ROLE OF MATHEMATICAL MODELING IN ROCK PROPERTIES EVALUATION AND APPLICATION

2.1 Introduction

A variety of models capable of representing the response of geologic materials will be necessary in repository studies. Several types of such models, now available, may be classified as:

Analytical

Numerical

Differential Methods	Finite element Finite difference
Integral Methods	Boundary integral equation Boundary element Displacement discontinuities (for thermo-mechanical analysis)

These are all essentially continuous models, even though special provision may be made to incorporate discreet discontinuties.

To discuss applicability of each type of model, it is convenient to break the repository design problem into four scales:

* Canister scale
* Excavation scale
* Repository scale
* Regional scale

Regional analyses, which must particularly concern long-term radionuclide transport, are influenced by the engineering design of the canister, excavation, and repository scale. A subdivision of less than regional scale analyses is given in Figure 5. Although many of these areas may already be studied using quite simple models, in the long term, more complex models must be developed to stages where they can be used with a high degree of confidence. Much model development specifically concerns treatment of interactions between fluid flow, heat transfer, and mechanical behavior. Possibly the highest level of coupling indicated in Figure 6 is not essential for repository design, given reasonable levels of thermal loading. That cannot be proven, however, until such analyses have been made and necessary laboratory and field investigations of phenomena identified for the coupled problem have been completed. In the meantime, much simpler analyses provide guidelines for experimental work on both laboratory and field scales as well as for preliminary repository design.

2.2 Model Applicability

2.2.1 Analytical Models

Analytical models are useful for large-scale or low-level analysis of detail. Such models assume linear behavior and therefore make minimal demands for input information. They make gross approximations and thus may be used at relatively low cost to perform sensitivity analyses. For example, they may be used to assess the magnitudes of stress changes in the vicinity of the repository in order to guide experimentation on the influence of stress on fracture permeability.

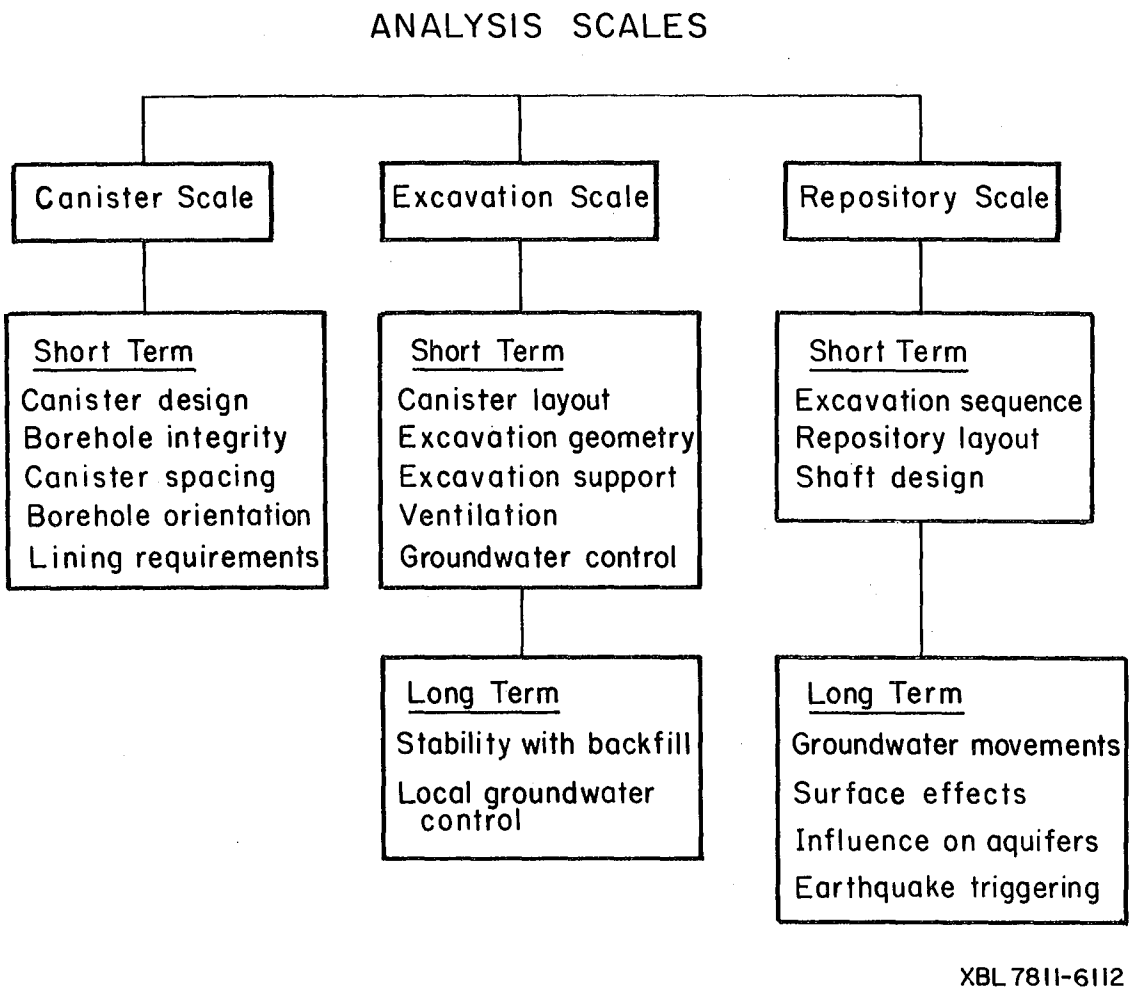

Fig. 5. Scales for repository analysis.

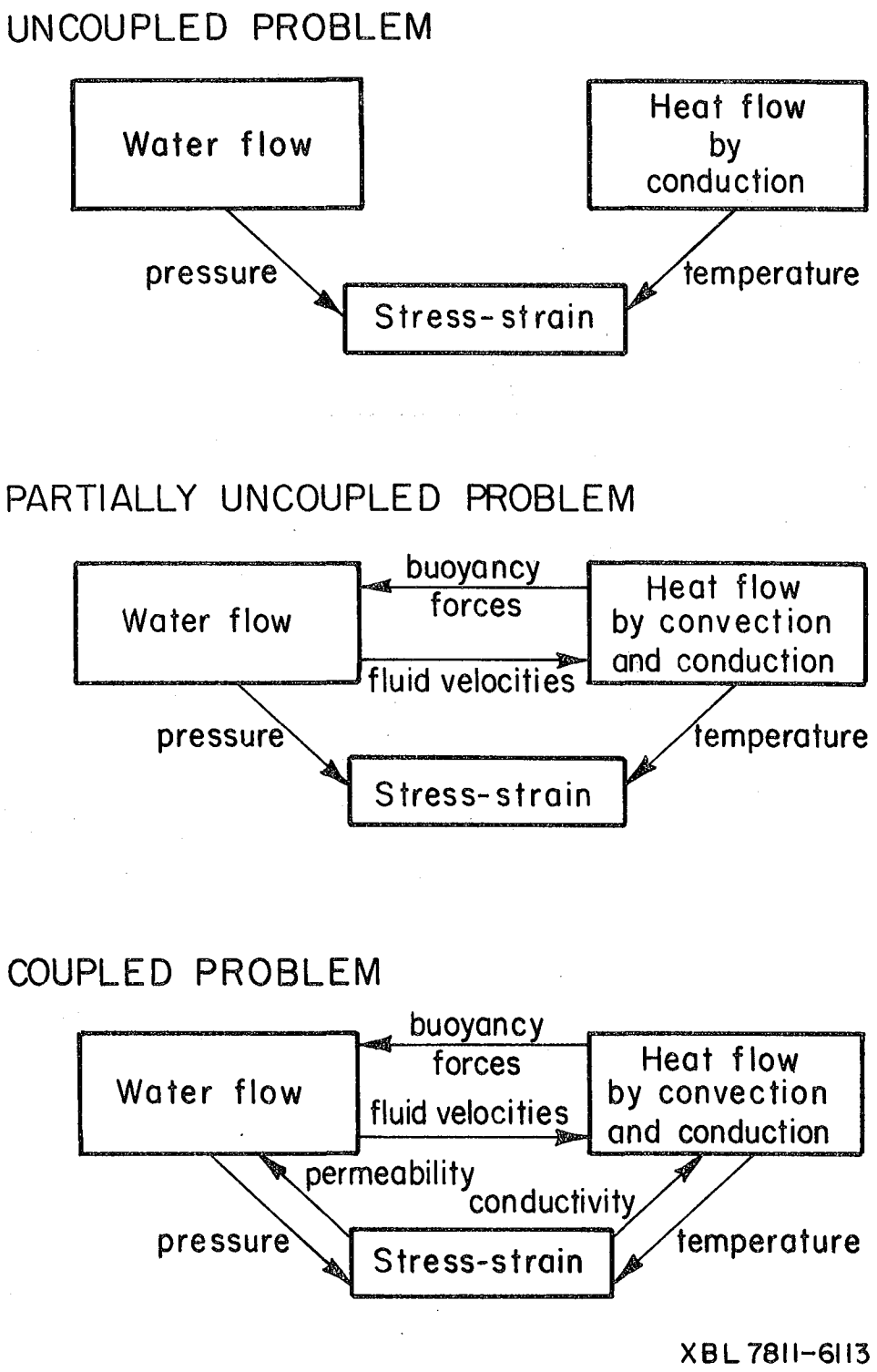

Fig. 6. Schematic representation of different levels of coupling in modeling.

Analytical models are also useful in many other areas, e.g., shaft design and prediction of surface effects.

2.2.2 Numerical Integral Models

Integral models are useful for analysis at intermediate levels of detail. Linear analysis of different excavation geometries, canister configurations, etc. may be carried out at relatively low cost. Because of idealizations made, integral models also make relatively modest demands for input information, and they are ideal for performing parameter studies on excavation and repository scales and for guiding repository design.

2.2.3 Numerical Differential Models

Differential models overlap considerably with the other types of models and should be used mainly when the approximations of the other models is not acceptable. For example, these models will always be used when complex nonlinear behavior and coupling between fluid flow, heat transfer and mechanical response are to be represented.

The type of problem that may be investigated includes borehole stability. For example, does borehole decrepitation result in a low thermal conductivity zone immediately around the canister? If so, what effect does this have on canister and rock temperatures? Needed input includes:

Thermal conductivity of broken material;

Relationship between stress and thermal conductivity;

Rock spalling criteria.

2.3 Modeling of Discontinuities in Rock Masses

The evaluation of the effect of discontinuities on repository performance will be of particular concern to those selecting the sites. Some special modeling techniques will have to be applied. All hard rock sites, at least, will invariably contain a multitude of cracks -- long contacts and faults, medium length shears, etc., down to dislocations in crystals. Depending upon the scale of the problem, the significance of individual members of this family may be negligible, significant, or over-riding. When the scale of engineering is far greater than the spacing between individual members of a set of discontinuities of a given length, some sort of averaging procedure is acceptable as a necessary approximation. However, if the dimensions of the problem are sufficiently limited relative to the spacing between individuals, then including individual discontinuities in a model will generally be a better procedure than forming of an 'equivalent' unjointed average material.

Despite soundly based objections to attempting to replace a network of discontinuities by an "equivalent anisotropic continuum", a number of examples confirm that this can be a valid procedure in certain instances. It should, however, be appreciated that the dilatant aspect of joint behavior is lost in such a procedure because the inclusion of dilatancy reduces the symmetry of truly "equivalent" anisotropic medium to such a low level that the approximate medium becomes intractable. At low normal stresses, dilatancy <u>is</u> important in understanding jointed rocks, especially as regards properties like fluid permeability and thermal conductivity that depend upon joint apertures. At high normal

stresses, i.e., above a normal stress equal to about half the unconfined compressive strength of the wall rock, dilatency is less important and can often be ignored. Then, at higher normal stresses, the substitution of an anisotropic continuum for the discontinuum is more acceptable.

Whatever the method of studying the coupled mechanical, thermal and hydraulic properties of rock, the constitutive theory necessary for simulation of the behavior of jointed rock is so complex that large scale in situ studies of sufficient number to acquire confidence will be required for verification of numerical analyses.

2.4 Modeling - Related Research Needs

There is an immediate need for comprehensive design studies for respositories in candidate argillaceous and crystalline rocks to identify limits for laboratory investigations and to identify critical areas in which research should be concentrated. Models sufficient for these studies already exist, although further development of models which account for complex interactions is necessary. Particular attention should be directed towards determining the extent to which a discontinuous material may be represented as an equivalent, possibly anisotropic, continuous material. Sub-developments must parallel appropriate laboratory and field experimentation and measurements.

Critical to the acceptance of a repository design is confidence in the models on which that design is based; i.e., confidence must be based on the demonstrated ability of models to predict the outcome of laboratory and in-situ experiments. It is recommended that such experiments should be conducted on both a canister scale and an excavation scale.

Experimentation and relatively short term monitoring unfortunately do not address the problem of confidence in predictions on very long-term scales. Indeed, it is difficult to conceive any experiment that could contribute significantly to increased confidence in predictions made over the time frames of concern. What might be of greater value is to identify geologic processes that are occurring on scales and times that are consistent with those of a repository. If models can be demonstrated to adequately simulate those processes, then their credibility will be significantly enhanced. It is recommended that current research on modelling appropriate geological processes be reviewed and stimulated if necessary.

Experiments should include monitoring of repository performance during its construction and operational phases. Monitoring and parallel modelling should also continue beyond the operational phase, for as long as necessary to ensure confidence over time spans more compatible with the duration of the high risk period of repository life.

3. SITE EVALUATION

3.1 Introduction

In this section the measurements which can best be carried out from boreholes during site selection and evaluation are addressed; discussion of measurements required during the reconnaissance phase, before any exploratory drilling, was omitted. While applicable airborne and surface survey techniques are perhaps adequate for the task, they are highly dependent upon the selection of a particular geologic and geographic province. In addition, the breadth of "remote sensing"

precluded a thorough discussion in the time allotted and therefore these methods were only considered in passing.

Most of our deliberations were directed at that sequence of events in the development of a repository commencing with the drilling of moderately deep (~1 km) cored boreholes on the regional exploration scale and continuing on through the drilling of more closely spaced boreholes for the investigation of a specific site. Within this context, attention was focused on physical measurements in boreholes, including the drilling but excluding in situ fluid pressure measurements (see also the Fracture Hydrology section.

During the discussions several points of a general nature were made which bear upon the overall borehole measurement problem:

a. Boreholes should be viewed as a means of gaining access to the rock rather than as entities in themselves. Hence, borehole methods which are effective over larger, more representative volumes of rock are especially to be encouraged.

b. Although the need for quantitative information is always stressed, it was recognized that in the early stages of site selection the ability to compare and rank may be just as important as the ability to quantify. In particular, the ability to locate and identify the "worst case" features, such as gross geological inhomogeneities or large fractures, will at first be of prime importance.

c. Since the purpose of drilling is to obtain information of a type not commonly sought in current practice, the drilling technique and core recovery methods deserve special consideration. Sets of parallel holes to facilitate cross-hole measurements, angled holes,

and splayed orientations should all be considered as techniques become available to take advantage of these geometries.

d. The topic of borehole plugging has direct impact upon the site evaluation drilling programs.

3.2 Geology

Once a potential site has been selected for investigation, the principal geologic factor to be investigated by borehole and remote sensing techniques is the gross (on the order of 10 m) homogeneity of the repository site (presumed to be a few sq. km). The homogeneity of the rock proposed for the repository influences:

a. The confidence with which one can assure the absence of features which might (if undetected) compromise the containment integrity of the repository during either operational or post-decommissioning phases.

b. The effort required to design, construct, and operate the repository.

The type of features considered here which might introduce significant inhomogeneity include faults or fault zones, intrusions in the host rock, facies changes, or weathered zones. The presence of any of these features may not eliminate a site from further consideration but they introduce (a) a degree of complexity in further work, and (b) implications for both short and long-term effectiveness of the respository.

Presently available techniques for evaluating repository-scale homogeneity of rock are generally adequate. Applicable remote sensing techniques include seismic reflection and refraction, gravity, magnetics,

and electrical methods. Procedures for determining homogeneity from a bore hole include core logging, various down-hole logging techniques, and cross-hole techniques. The down-hole and cross-hole techniques in general use today utilize tools designed for NX holes (nominal 3" diameter) or larger. Some work will be required to modify and calibrate these tools for use in the slim holes contemplated for preliminary repository site investigation. Especially lacking is experience in well log interpretation in igneous and metamorphic rocks. For this reason it is recommended that boreholes be drilled at several sites where the rock is typical of what would be desired at a repository site.

3.3 Core Drilling Procedures

The initial view of subsurface conditions at a potential repository site will be provided by examining the cores and collecting data in the boreholes created by diamond drilling. There are many tools available for creating such boreholes, some of which are listed below:

Tool	Characteristics
Single tube core barrel	Core is exposed to both flushing water and drill rotation
Double tube core barrel	Core is exposed to flushing water but not to rotation
Triple tube core barrel	Core is not exposed either to flushing water or to rotation
Triple tube core barrel (split inner tube)	Inner tube can be opened up to expose the core
Wire line triple tube core barrel	Core barrel can be removed without pulling the drill string

The core barrels are listed in order of increasing cost and improved protection of the core. To date, in at least crystalline rocks, the single and double tube core barrels are the most commonly employed in mining and civil engineering applications. The results have generally been satisfactory for achieving good core recoveries. Unfortunately, most, if not all, of the details regarding discontinuity surface conditions are lost by these simple procedures. It is precisely this information which is of most interest when evaluating potential repository sites. Thus the requirements are considerably greater than for the usual projects, and special drilling techniques and approaches are needed. A partial list of such special requirements is given below.

a. Cores must be obtained in as undisturbed condition as possible. This requires preserving orientation and spacing of fractures and joints, moisture conditions, condition of matrix material, and condition of filling materials.

b. Ground water contamination by drilling fluids must be minimized and any effects must be determinable.

c. The condition of the borehole wall should be as undisturbed as possible so that optical examination and geophysical probing opportunities are enhanced.

The following research/development projects are recommended to maximize the possibility of data collection from exploration boreholes:

a. Evaluation of drilling fluids that minimize disturbance and contamination.

b. Evaluation of special procedures and tools for retaining moisture conditions and pore pressures of cores.

Some work is presently under way in the petroleum industry to achieve this same purpose, however, they are intended generally for larger diameter holes (4" to 8").

c. Evaluation of reaming and/or surface preparation tools which might enhance quality of borehole wall conditions for optical and geophysical observation techniques.

d. Continued development and refinement of special procedures such as described by Rocha (1971) for pinning together the future core in the hole prior to coring. This technique allows the actual measured joint apertures and other properties to be correlated with those obtained from later hydrological, geophysical, and mechanical borehole tests. This "integral sampling" would provide calibration data for borehole logs.

e. Development of practical strategies in which one hole would have a series of deflected holes drilled from it. This would minimize the amount and cost of borehole drilling and plugging and maximize the possibility for cross hole determinations at repository depth across varying distances.

3.4 State of Stress

The state of stress in crystalline rock is of central importance to the disposal question because it affects not only the mechanical stability of the repository, but also the potential for slip, seismic activity, and permeability changes along existing fractures. Also, the potential for initiation of new fractures due to thermal stresses generated by the waste is inextricably linked to the state of stress

in the rock mass. Because of its fundamental importance, stress measurement is also discussed in other sections of this report.

Attempts to determine stresses in rock have been made for several decades; although a variety of techniques involving borehole observations have been tried, none has been broadly accepted as proven. In all cases the stress state is deduced from an observable effect of stress change (e.g., elastic wave velocity, resistivity, core discing, strain, fluid pressure necessary to hold open a fracture, etc.). Uncertainty about the complexity of the relationship between the stress and the observed effect is in all cases a major obstacle to the development of a reliable technique, and simplicity of the relationship is a desirable feature of any potential method. Two main categories of methods in use are overcoring and hydraulic fracturing. Overcoring is perhaps more precise, but hydraulic fracturing is the only current way to determine stresses at depths greater than 20 to 50 m in a borehole. For both methods, significant objections can be raised with respect to the validity of the simplifying assumptions made in interpreting results of measurements.

Relatively little research of a sustained, thorough nature has been carried out to improve these or other methods. Because of the importance of knowing the in situ stress conditions in the waste disposal question, it is recommended that such research be conducted on borehole methods of stress determination. This research should include:

a. Development of a facility for application of known triaxial stress to substantial rock masses (e.g., 1 metre cubes) of different types for study of the accuracy of various methods of stress determination (Bonnechere, 1967).

b. Study of possibilities for determining stress from a borehole over a representative region of the rock mass (e.g., variability along the length of the hole, as an indication of changes in other directions) via measurement between boreholes, or in fractures extended from a borehole by hydraulic fracturing.

c. Development of down-hole tools and recording packages for stress determination at depths up to 500 m or greater. Such research should be directed more towards development of techniques capable of identifying stress regimes, e.g., low, moderate or severe with respect to rock mass strength, than to precise specification of stress magnitudes at definite locations in boreholes. There may, for example, be discernible differences in acoustic signals between boreholes for each such region, or in signals received in one borehole due to fluid pressurization in another.

3.5 Fractures and Other Discontinuities

The specific contributions of a system of discontinuities to a rock mass are many. Discontinuities change all the rock mass properties, usually to make the rock more deformable, weaker, more permeable, and more conductive. Secondly, depending upon the arrangement of the members of the different sets of discontinuities, the rock mass is rendered anisotropic in all properties. Thirdly, all properties of the rock mass become highly stress dependent. As a result of these interactions, all sites in jointed rock are unique and conclusions drawn from study with one site require replication in order to permit firm engineering conclusions. Generic studies are thus of limited value.

Though it is necessary to examine discontinuities of all spacings as regards repository design, it is probable that the discontinuities of great length are more important than those of short length. The number of discontinuties decreases, however, as the length increases. The compounding of these effects suggests that discontinuities of medium scale, perhaps of the order of ten to twenty meter spacing, will probably play the most important role in repository engineering, since the vitally important long, widely spaced discontinuities can be omitted from the repository region by judicious layout.

Borehole measurements of fracture parameters prior to construction of the repository are the least expensive means of obtaining pertinent information. Core analysis and description, the method most commonly used, depends upon quality of core and hence upon the quality and type of drilling method and the degree of disturbance to the core. Alternative methods of borehole measurements, including electrical, optical, and acoustic, are discussed below.

3.5.1 Single hole methods

Electrical resistance method -- "electrical caliper" -- has been successfully used in slim holes of various diameters. Experience from Sweden shows that this method is capable of detecting individual fractures and their frequency. This method, however, does not measure fracture aperture or fracture orientation.

Optical methods include mainly (a) TV logging equipment for both short and long boreholes, and (b) the borescope, which is limited to short boreholes. Although optical equipment can detect locations of fractures, their frequency and their apertures, image quality and

resolution is often very poor; interpretation can be very subjective in some instances.

Acoustic (ultrasonic) methods, which measure propagation of shear and compressional waves, might be used to detect fractures and their apertures, frequencies, and orientations. This method has been used both in-hole and between-holes (see the next section), thus giving better information on fractures and their behavior in the rock mass between boreholes. This represents an advantage over the optical method which cannot penetrate beyond the borehole walls. Since acoustic methods cannot presently do more than detect whether a fracture is open or closed, fracture aperture must be measured in another way.

It is felt that some combination of optical and acoustic methods offers promise for the detection of fractures in a single borehole. The electrical method deserves consideration because of its instrumental simplicity and its response to the fluid in the fracture.

3.5.2 Cross-hole Elastic Methods

The objective of measuring the elastic properties of a rock mass is to ascertain moduli of bulk rock, fracture frequency, and fracture aperture. It is important to measure these parameters for two reasons: (a) to get an absolute knowledge of the properties within a potential respository, and (b) to get base line data for monitoring increase or decrease of stress of the rock mass.

The current technology of dynamic mechanical property measurements at depth is limited to down-hole sonics. The problem with this method is that it measures in a very small volume near the borehole.

Cross hole techniques for dynamic in situ determination of elastic properties should be developed. The advantage with such a method is that it measures a large undisturbed volume of rock. The cross hole method should be developed to work in holes with spacing between 20-500 m. The two extremes place different demands upon instrumentation; different input energy and different portions of the frequency spectrum may be needed for the different distances. Through wave train analysis we should be able to measure the amount of fracturing in the rock mass and the aperture of the fractures in the area. Wave train analysis implies spectral analysis as a function of the number and aperture of fractures and their water content.

This method should be used both in the site evaluation and also in the repository operation phases.

3.6 Porosity

A few definitions will be necessary before proceeding to a discussion:

a. Total porosity -- the ratio between the total volume of voids and the total volume of rock including voids.

b. Effective porosity -- the ratio between the volume of water which can be put in movement under the effect of gravity forces and the total volume of rock. It does not include water adsorbed at the surface of grains or fissures. Some rock, e.g., shales, may have a very high total porosity and a very low effective porosity. Effective porosity is one of the parameters governing nonsteady state flow of groundwater.

c. Interconnected porosity vs. non-connected porosity -- Porosity is interconnected if the voids are in communication with one another; non-connected porosity plays little or no role of radionuclide transport.

d. Matrix vs. fissure porosity -- Porosity should not be defined by only one figure; a cumulative or differential curve giving the distribution of pore dimensions of interconnected porosity should also be given.

A variety of techniques has been applied to the measurement of porosity for oil reservoir assessment, including acoustic velocity, electrical resistivity, neutron, and density measurements. All four of these techniques are currently available in small-diameter borehole probes, but little work has yet been done to assess and compare the accuracy and sensitivity of these four methods. The neutron-thermal neutron probe can measure the water content of granite at porosities less than three volume per cent. A resolution somewhat better than 0.5 volume per cent can be obtained, depending upon the averaging time and logging speed. However, the technique measures the total water content of the rock, both water in pore space and water which is mineralogically bound. Another problem with the slim-hole neutron tool is sensitivity to hole size changes. The resistivity method is applicable in low porosity crystalline rocks in the sense that Archie's law applies, but its sensitivity limitations in fractured media are unknown. The same limitation is expected to be true for the density method in that, at least to first order, porosity controls the density fluctuations if grain density is constant. Acoustic velocity is expected to be less effective, except possibly in unfractured

rock. Of these methods, electrical resistivity offers the best chance of distinguishing effective porosity.

From a knowledge of interconnected porosity and pore size distribution it should also be possible to determine the specific surface, one of the factors governing adsorption phenomena. Conversely, from the knowledge of specific surface and pore size distribution it should be possible to determine the interconnected porosity.

If either a "fissure" model or a model taking into account both matrix and fissure is used, a numerical distinction between the effective matrix and fissure porosity must be made. In the latter model, a minimum fissure size is designated in the model below which size fissures are considered as part of the matrix or the equivalent continuum. In actual fissure flow simulation, porosity of fissures is not used as such: the geometric parameters of each fissure, i.e., aperture, continuity, and roughness, are used. These are, of course, related to fissure porosity.

It is difficult to determine the fraction of the "global" effective porosity concerning the matrix and small fissures as opposed to the total effective porosity including all fissures. This question may be academic, provided that if only large fissures are treated individually, their porosity is negligible compared to the porosity of the matrix and small fissures. The former could probably be assumed to equal zero, and the second assumed to equal the "global" effective porosity.

Porosity, and especially the pore size distribution, will be a very important factor for the choice of the appropriate injection mixture if grouting is to be used to plug the borehole.

3.7 Permeability

Permeability controls the flow of fluids in rock and hence the possible migration of radionuclides to the biosphere. Permeability is one of the more crucial, if not the most crucial, factor to be assessed. It is also one of the more difficult to assess. In this section methods of measuring permeability which rely upon the injection or withdrawal of fluids are not considered since these techniques are discussed in the Fracture Hydrology section. Instead, three possibilities for the indirect determination of permeability are discussed. These approaches are quite speculative at this time; in fact, it was felt that any indirect method based on estimation of fracture aperture or on inference through electrical properties will be difficult to demonstrate and implement. Nevertheless, permeability is so important that any reasonable proposal which could lead to a quick estimate should be seriously considered.

Three physical methods offer some appeal as a permeability estimator. Electrical current flow is attractive because of continuous, linked flow occurring within the rock. The limiting assumption is that the current flow paths closely approximate fluid flow paths. For fracture permeability, one faces the problem of configuring the excitation to planar geometries. Another technique under development in the petroleum industry is the nuclear magnetic resonance method. This method is attractive because it responds to the presence of free water. A third approach might be to introduce "sloshing" by some mechanical or hydraulic means and detect the response.

There does exist one field-proven method for quickly and accurately locating permeable zones, although the permeability cannot be quantified. In the petroleum industry this method is called "flow profiling", whereby a flow sensor is towed through the moving fluid in a borehole. The "moving" of fluid is due to injection or withdrawal at the wellhead; changes in flow rate are then detected as the tool passes a zone where fluid loss occurs. At the present time, flow sensors include the spinner log and the radioactive tracer log. For this application, there are objections to the radioactive tracer log, however, and the best spinner log currently in use has a sensitivity to changes in flow velocity of several feet per minute. Hence an order of magnitude or more improvement in tool sensitivity is necessary and availability in small diameter configurations is desirable.

In summary, promising techniques for the indirect assesment of permeability should be highly encouraged. Improvement in flow tool design appears to be a low-to-medium priority item.

3.8 Exchange capacity

Exchange capacity measures the ability of an adsorbing or porous medium to remove ions of a particular species from solution. As such, it is an important parameter in considering the ability of the host rock to retard migration of radionuclides. Exchange capacity is measured in commercial service laboratories for the petroleum industry, where the information is used to correct porosity estimates made from electrical resistivity logs. This parameter could conceivably also be estimated in situ on a continuous borehole log. The induced polarization (IP) method, which measures the phase shift of low frequency electrical

current flow, is a promising approach to indirect measurement since it is well known that clays and zeolites produce a polarization response. Hence correlation between exchange capacity and IP response should be examined. For geochemical modeling, however, far more complex measurements are necessary (see the discussion in the report of the Geochemistry panel.)

3.9 Background Radioactivity

Background radiation measurements from geologically deposited U, Th, and K yield historical data on concentration of these elements along the length of a borehole in a potential repository. At a later time, integrity of the repository can be checked by comparison with the virgin data. A side benefit of spectral gamma logging is the information obtained on geological inhomogeneities.

Identification of low-level radionuclide radiation in the environment is performed by a high-sensitivity gamma-ray spectrometer. The system consists of a high efficiency scintillation detector, a high gain photomultiplier, and a multichannel analyzer. The system should exhibit a response proportional to the energy of the incident radiation. Thallium-activated sodium iodide, NaI(Tl), is the most efficient and extensively used scintillator for gamma-ray detection. The high atomic number of sodium iodide gives a large ratio of photoelectric-to-Compton effect and is thus desirable for spectrometry application. In addition, light emitted from the material lies in a spectral range which is particularly well matched to the spectral response of conventional photomultipliers.

NaI, however, is highly sensitive to moisture, thermal shocks, and thermal gradients. Newly developed rugged units which are hermetically sealed in stainless steel containers can operate at temperatures from -20°C to 200°C, although associated photomultipliers generally do not presently operate above 105°C. If detailed knowledge about a particular radionuclide in necessary, a NaI(Tl) detector has insufficient resolution to separate closely spaced peaks in the spectrum without extensive pre-analysis chemical separation. In such cases large semiconductor detectors can be used. Operating temperatures range from room temperature for silicon detectors to 80°K for germanium detectors. For higher operating temperatures new solid state detectors should be developed.

The uranium exploration industry and associated governmental agencies are currently marketing three-channel spectrometers and improving the instrumentation. In addition, a spectral gamma logging service is commercially available for the larger diameter boreholes used by the petroleum industry. It should therefore by relatively straightforward to adapt existing technology to the small diameter, deep (~2,000 m) boreholes contemplated for waste disposal.

3.10 Thermal Conductivity

The rock mass in the vicinity of a repository will be subjected to heating from the radioactive materials. The rate of heat flow, thermal stresses, etc., will depend on the thermal conductivity of the rock mass. It seems adequate to determine thermal conductivity of the rock using core taken from the region, provided that due consideration is given to the possible influence of fractures induced by drilling and removal of the core from depth.

4. LABORATORY ROCK PROPERTIES MEASUREMENTS

4.1 Introduction

The need to isolate high-level radioactive waste from the biosphere for periods of $\sim 10^6$ years requires location of a rock mass suitable for the necessary containment and thus requires development of a predictive capability unprecedented in engineering. Such a predictive capability can be achieved only by developing "realistic" mathematical models, using our short-term observations and experiments, that simulate the relevant geologic processes and their complex interactions. Thus the role of laboratory testing of rock specimens is twofold: (1) to provide understanding of the mechanical behavior of rock under conditions likely to exist in the region of a geologic repository, without which a realistic model cannot be developed; and (2) to provide input data to the model and to place bounds on values of relevant parameters.

Rock properties evaluation and modelling is pertinent to two different but related aspects of repository development. The first concerns stability of the mined cavity during the operational period, in which the repository will be occupied by personnel and equipment, and during which it will be relatively easy to retrieve emplaced canisters. The second concerns the mechanical response of rock in the far field, particularly in terms of permeability effects.

In the short-term operational phase, perhaps lasting several decades, strength and time-dependent behavior can be important factors; in the post-operational periods, however, ductility and the ability of rocks to deform without fracturing can be more important. Prediction

of behavior during the post-operational period may be more difficult: this period is characterized by a thermal pulse that extends from the time of emplacement to the disappearance of the more signficant heat-producing radionuclides. The maximum in the pulse is reached, however, in less than 100 years. The fission products of concern largely decay after about 600 years in reprocessed waste, but the burial of spent fuel elements could extend the thermal period significantly, owing to the presence of heat-producing actinides.

A distinction must be made between properties of the intact rock and those of the rock mass with its included fractures. In general, the strength, thermal conductivity, and thermal expansion will be significantly lower for a rock mass than for intact specimens. Laboratory tests performed on small samples can thus provide upper bounds on the values for such parameters under specified conditions.

4.2 Types of Laboratory Tests

Laboratory tests provide the sole means of evaluating the behavior of rock under a wide range of controlled conditions. Most laboratory tests, however, are presently subject to two limitations:

a. With few exceptions, the largest specimen dimension is <25 cm. For tests at elevated temperature, the largest sample dimension is about 10 cm.

b. It is very difficult to study samples of rock which contain natural fractures. These limitations imply that laboratory tests are mainly useful to ascertain the properties of intact rock. To evaluate the behavior of fractured rock, recourse is generally to artificially fractured rock, block-jointed

samples made of model materials, in situ experiments, or mathematical modeling.

The restriction of specimen size in laboratory experiments introduces uncertainties which have to be considered before laboratory measurements are used to assess the response of rock masses. The behavior both of intact rock and of discontinuities may depend on specimen size -- it is frequently stated that scale effects of intact rock properties are caused by inhomogeneties in rock texture and composition and by the presence of small fissures and microcracks. Some fractures might be eliminated with decreasing specimen size, thus changing the measured rock response. In turn, scale effects of discontinuities are attributed to surface characteristics of the discontinuities, e.g., waviness and roughness.

If we include small-sized (3 m or less) in situ experiments, there are six common types of test: 1. direct shear; 2. triaxial; 3. biaxial; 4. in situ; 5. multiaxial; and 6. tension.

The maximum sample size, conditions attainable, and properties measurable are listed in Table 2 and aspects of the testing methods are discussed below. In situ methods are included here because when conducted on meter-sized samples they become, in effect, a laboratory study.

Methods most appropriate for waste disposal problems are presumably those applicable to fractured rock and those in which thermoelastic properties, thermal and fluid conductivity, frictional behavior and perhaps tensile strength can be evaluated under chemical and environmental conditions representative of depths from 0.5 to 2 km. Because of

Table 2. State-of-the-art Summary of Rock Property Tests.

	Maximum Sample Size	Stress State*	Temperature	Fractured Sample	Properties Measured	Example
Direct shear	0.3 m	$P_c, P_p \leq 1$ kbar	25°	yes	friction, k V_p, V_s, d_n, d_s	Goodman, UCB
Triaxial	1 m 10 m 1 cm	$P_c, P_p \leq .5$ kbar $P_c, P_p \leq 4$ kbar $P_c, P_p \leq 10$ kbar	25°C 200°C 1000°C	yes yes yes	Fracture, friction V_p, V_s, k, strains, creep, thermal expansion conduction	Byerlie, USGS Botters, TTI, Heard, LLL
Biaxial	2.0 m	$P_c, P_p = 0$	25°C	yes	Friction, V_p, V_s	Dieterich, USGS
In situ	3 m	$P_c, P_p = 0$	25°C	yes	Fracture, friction V_p, V_s, k, displacements	Pratt, TTI
Direct and indirect tension	.3 m	$P_c, P_p = 0$	400°C	n.a.	tensile strength V_p, V_s, strains	
Multiaxial	10 cm	$P_c \leq 1.5$ kb	600°C	no	fracture, V_p, V_s, k displacements (?)	Kern, Ukiel

*P_c = confining pressure; P_p = pore pressure

local heating by the waste, properties must be studied at temperatures ranging to a few hundred degrees Celsius.

Fractures dominate all of the above properties with the possible exception of thermal conductivity of water-saturated crystalline rocks. Fractured rock, when more than a single fracture is involved, can only be studied in situ and then only at surface pressure (P) and temperature (T). Thus naturally fractured rocks probably do not presently fall into the domain of laboratory testing. Although P and T cannot be controlled in in situ tests, important insight can be gained into the general role of fractures and into mechanisms. Laboratory tests with a single fracture can be compared with in situ results at all scales. From the table, four methods can be used for single-fracture studies; because of the wide range of conditions attainable, the triaxial method may be most suitable. Some work (Witherspoon et. al., 1977) suggests that samples 1 m or larger must be studied to obtain meaningful values of rock masses. We discuss such experiments in section 6.6.

4.3 Test Parameters

The following parameters are probably the most significant for repository design as presently understood: stress state, temperature, time, rock type, and fracture and discontinuity characteristics such as surface character, aperture, and infilling. In addition, factors such as the stress, deformation, temperature and radiation history might be important.

The depth of a conventional mined repository will likely not exceed 1500 meters. Available in situ stress measurements indicate that the minimum principal stress prior to mining at such depths is likely

to be under 30 MPa. Laboratory triaxial tests need, therefore, to explore the influence of stress state under confining pressures (minimum principal stress) to up 30 MPa.

If the peak rock temperatures in the vicinity immediately surrounding the waste do not exceed 300-400°C, the far field temperature will be less than 200°C and may not exceed 100°C. For this reason evaluation of thermally induced stresses is most critical during the first few hundred to thousand years, depending upon whether high level waste or spent fuel elements are emplaced in the repository.

5. EVALUATION OF ROCK PROPERTIES BY FULL SCALE IN SITU TESTING

5.1 Introduction

In situ determinations of rock mass response to mechanical and thermo-mechanical loading are requisites for the geotechnical assessment of a repository. In this section the properties that need to be measured, the anticipated environmental conditions under which the properties should be measured, and the current state of the art in measuring these properties are considered. The panel recognized the need for both generic and site specific test programs to assess potential crystalline rocks and argillaceous rocks to give confidence in evaluating repositories at depth. The panel proposed that an Underground Test Facility be excavated in an environment (depth, rock type, geologic conditions) similar to that anticipated for a repository. Rock mass properties would be measured before, during and subsequent to excavation and during thermomechanical experiments. Some tests would be taken to failure if possible. A Confirmatory Test Facility will be required at each actual repository. Even with such testing many years of

continuing site evaluation will probably be required, during which time the repository could be in operation, before confidence in long-term containment is achieved. This required that retrievability be assured over long time periods should predicted and actual rock mass behavior diverge.

5.2 Characterization of Rock Masses

5.2.1 Structural Geological Mapping of Experimental Openings

The structural geology of the rock mass which surrounds the experimental openings is fundamental to interpretation of tests of the rock mass in situ. This information will be required to interpret the structural stability of the openings from both mechanical and thermo-mechanical standpoints. In addition, this information will be required to assist in measurement of hydraulic properties. A structural geological mapping program of the experimental openings will describe the variations in the rock matrix and in the spatial relationship of discontinuities which intersect and therefore influence the performance of the openings. This section briefly describes the features required to be observed, comments on the 'state-of-the-art' and suggests methods of presenting the data.

The description of intact rock would include details of the minerals which make up the matrix, grain size, nature of grain boundaries, nature of pores separating individual minerals, inclusions, etc. Description of the discontinuties which intersect the openings should include:

* The location and attitude of each feature.
* A broad categorization of the extent or persistance in two dimensions of exposed discontinuties, e.g.:
  a. those discontinuities which may be traced on one side, over the back, and to the other side;
  b. those discontinuities which may be traced on one side and the back; and
  c. those discontinuities which may not be traced beyond one side.
* The nature of exposed intersections between discontinuities and terminations.
* The aerial persistence of discontinuties.
* The roughness or tortuosity and aperture variation.
* A distinction, where possible, between natural, mining-induced, and stress-induced discontinuties. Changes as a result of tests should be measured.
* The nature and variability of infilling materials located in discontinuties.

It is felt that the majority of these requirements are within the state-of-the-art with the exception of describing the areal persistence of discontinuities, describing tortuosity, evaluating aperture variation, and distinguishing among natural, mining, and stress-induced discontinuities and the measurement of these changes. The methods of recording (line sampling, photographic, etc.), where access is possible, can clearly be amplified by radial boreholes drilled after openings are made.

The ability to predict the performance of openings using data from cored boreholes orientated down the axis of the proposed opening is not good. Such pilot holes should not be smaller than NX in diameter and triple tube drilling or equivalent would be required. On completion of boreholes, structural examination of the annulus to measure some of the features listed above is possible and desirable.

5.3 In Situ Stress Measurements and Stress Monitoring

5.3.1 In Situ Stress Measurements

Any rational mechanical or thermo-mechanical analysis or design of an underground excavation must proceed from an assumed or measured in situ state of stress. Excavation, mechanical loadings, pressure changes, or thermal loadings are merely perturbations on this existing initial state of virgin stress. Most failure criteria or rock mass mechanical characteristics are expressed in terms of the state of stress. Any attempt at design requires knowledge of both the existing state of stress at any point and the failure criteria of the rock mass.

At this time we can make reasonable measurements of the in situ state of stress in elastic and effectively continuous rock masses from relatively short (<100 m) boreholes using strain-relief techniques. We can estimate the minimum principal stress magnitude and direction from deep boreholes by hydraulic fracturing techniques. Maximum horizontal stress can be only approximated using the field test data and laboratory properties. The virgin state of stress at a point in a rock mass is the result of superposition of several independently acting stress fields.

These fields include stresses due to gravity, tectonic activity, thermal gradients, mechanical inhomogeneties and the residual stress field. Separation of the residual stress field, in particular, is at present very difficult.

Research needs include (1) Development of a stress relief or stress compensation method workable in deep boreholes; (2) Continued improvements in techniques, equipment, and understanding of hydraulic fracturing techniques to make interpretation of the maximum and intermediate principal stresses more reliable; and (3) Work in the whole problem of the origin, measurement, and separation of residual stresses.

Preexisting fractures in rock masses are not necessarily related in any way to the currently existing in situ stress field: they are generally indications of the paleostress field existing at the time of the formation of the fracture. The current in situ stress field may be simply a relaxed version of the older residual stress field or it may be totally different. Any particular mass of rock may have gone through several independent stages of deformation and/or fracture before being exhumed and placed at or near the surface of the earth.

5.3.2 Stress Monitoring

Stress monitoring is required for much the same reason as virgin stress measurement. We need to know the state of stress at every point in the rock mass as a function of time if stability is to be assessed.

The state of the art is that the reliability of our instruments is inversely proportional to some power of the time since they were installed. Commercial stress monitoring devices are available and

a few types placed in concrete and in soil embankments have apparently been stable for periods of a year or more. Most rock mechanics practitioners would agree that none of the currently-available instrumentation is suitable for rock stress monitoring for more than a year. Developmental research is needed to improve exisiting techniques and make them more reliable over longer (~10 years) time span.

5.4 In Situ Mechanical Properties

5.4.1 Large Scale In Situ Tests

Large scale in situ jacking and pressure chamber tests have been conducted for several years and several types -- flatjacks, uniaxial jacking, and radial jacking -- will be considered here. These tests primarily have been used to measure deformation modulus. Measurement of deformation, permeability change, velocity change and electrical properties have been made as a function of stress and stress state (unaxial, biaxial, shear) in only a few cases. No tests have been made of temperature as well as deformation field. Flatjack tests with heaters need to be conducted.

5.4.2 Time Dependent Properties of Rocks

Rock masses behave in a time dependent manner due to crystal gliding, moisture effects, crack generation and growth, and in inherently viscous components, e.g., clays. Creep is not normally significant in crystalline silicate rocks at low stresses but at great depth the possible degradation of a site due to creep has to be considered. Of particular importance is the creep enhancement associated with increased temperature. Little is known about this in terms of primary and secondary creep rates and criteria for onset of tertiary creep, except in relatively few

laboratory experiments with simplified stress conditions and in mines in a number of evaporite rocks. For the repository design, it is vital to secure reliable data from in situ tests where loads are maintained over several months or longer, both before and after increase in rock temperature. Flat jack tests, dilatometer tests in boreholes, and plate bearing tests are suitable for such purposes. Pressures can be maintained over long periods by connecting the hydraulic cylinders with a column of fluid under its own weight. These types of tests are recommended.

5.5 Thermal Effects

Temperature fields must be measured to required accuracies and temperature measuring systems must fall within required stability and reliability tolerances over the life of the experiment.

5.5.1 Thermal Cracking

It is well known that rocks fail when subjected to thermal extremes or gradients. Any fracturing which occurs around a waste package will contribute to the fracture porosity and permeability of the rock.

The mechanisms of thermal fracturing are not well understood but they involve anisotropic expansion or contraction of individual grains in a monomineralic rock in a uniform thermal regime, unequal thermal expansion of the various grains in a polymineralic rock in a uniform thermal regime, and uneven expansion of the minerals in any rock due to temperature gradients and spalling or intragranular fracture due to extreme temperature gradients. In addition, residual stresses probably play an important role and they themselves may be the result of a previous thermal event.

A research program is needed to evaluate these individual effects.

5.5.2 Thermal Expansion of Jointed Rock Mass

Comparison of predicted temperatures and thermally induced displacements based on a simple continuum model with initial results of the heater tests at Stripa indicates that although the temperatures are in reasonable agreement, the measured displacements are considerably less than predicted. It is suspected that the rock matrix expansion is absorbed by closing of joints. It is necessary, therefore, to heat a large block of rock a few meters in dimension to measure the bulk volume change. This would allow an equivalent bulk thermal expansion coefficient to be obtained for use as input in thermomechanical models.

5.6 Rock Reinforcement

It is important to conduct research on the assessment and/or development of methods of rock reinforcement to insure underground room stability. Both short and long term time scales should be considered. The short term includes that time which an excavation must be kept open for canister retrieval purposes. The long term includes the period after backfilling and repository decommissioning. During the retrieval period, which could be tens of years, the rock mass temperature could be in the range of 100 to 300 ^{o}C and the performance of rock support systems, such as resin grouted belts, is not known under these conditions. Testing should be conducted either in the laboratory or during in situ testing to assess support performance. Additional requirements based on canister retrieval equipment and operations will determine the degree of support needed. During the long term, the performance of rock reinforcement systems

is not critical. Backfilling will provide support against major excavation collapse.

5.7 Underground Test Facilities

5.7.1 Introduction

The near-field thermomechanical response has to be understood in order to ensure retrievability. Retrievability depends upon the layout of the waste canister array, the initial power and age of the waste, the design of the canister assembly, design and control of the boreholes in which the waste is emplaced, and the operational sequence of emplacement. Since the behavior of rock mass containing discontinuities is poorly understood, the only credible way to assess the thermomechanical response of the rock mass is to carry out in situ heater experiments using electrical heaters with geometry and power similar to the waste canisters. In our opinion, no radioactive material should be emplaced until a number of heater tests have been completed.

The objective of these electrical heater experiments are:

a. To provide data for temperatures and thermally-induced displacements and stresses expected in the near-field in site(s) geologically similar to the potential repository.

b. To obtain in situ thermal and mechanical rock properties and failure criteria if possible.

c. To confront theoretical models, identify additional details to be incorporated into models and (hopefully) validate improved models.

5.7.2. Heater Tests Presently Underway and/or Planned

As background, the panel discussed the programs currently being conducted in the U.S. and foreign countries in crystalline and argillaceous rock:

Sweden: KBS--Lawrence Berkeley Laboratory--granite

England: Cornish experiment--Harwell--granite

U.S. Nevada Test Site:

Lawrence Livermore Laboratory--granite

Sandia--argillite (shale)

U.S. Hanford Reservation: Rockwell--basalt

U.S. Oak Ridge National Laboratory: Sandia--shale

It is recognized that many results of rock mechanics research change markedly at approximately 100°C. Above this temperature water boils at ambient conditions and grossly affects rock properties. Many dehydration reactions occur in phyllosilicate minerals and thermal cracking may be initiated. As temperature increases above this level the complexity of these responses increases. Even though the response of rock is simpler below 100°C, it is still complicated and effects of pore pressure, in situ stress, etc. must be considered. Therefore an important suggestion is that canister loading of a repository should be designed to keep rock temperatures below 100°C.

5.7.3 Possible Sites

Tests in different rock types can indicate potential areas for a repository, and a number of potential rock types must be considered. For crystalline rocks this implies tests in granites to ultrabasic rocks. Further, we have to consider rocks with different amounts

of deformation and metamorphism, e.g., granites, granitic gneisses, and gneisses. Any combination of these groups is possible. A similar approach should be applied to argillaceous rocks.

The heater tests in the near future, however, should not be located in the potential area for storage, since we cannot closely predict at the present time the effect of the disturbance introduced into the area. After initial tests outside potential repositories have been evaluated, similar tests can be implemented in potential repository sites. The near field heater test should be conducted in all stages of waste handling procedures except for backfilling.

5.7.4 Test Plan

Heater tests with and without backfilling of the holes can be conducted in different stages of complexity. The following sequence is recommended:

a. Pilot experiment with a simple heater and a few instruments for measuring temperatures and displacements, e.g., the pilot heater test at the Stripa mine.

b. Full scale heater experiments with extensive instrumentation for measuring temperature, displacement, stress, and fluid flow, e.g., the ongoing heater test at the Stripa mine.

c. A large number of heaters with the most essential instrumentation. In this sequence, the design of each test is based on the results of the previous test. After the first two steps we should be able to compare the results to theoretical models and improve the models. If the results of the third step confirm

the improved model this would give us confidence in predicting the near-field behavior of the repository.

Because of the uncertainty of our current knowledge of subsurface media and their inherent variability, it is important to question how much data must be gathered to insure that several thousand canisters of radioactive waste can be safely disposed of underground. Clearly, a handful of experiments conducted over a few years at one site is unlikely to provide information covering a sufficient range of conditions in space and time to provide the requisite degree of assurance. The confidence attached to data gathered from heater experiments would be enhanced vastly if their number were increased at several different potential sites for a period of a few years. However, would even several heater-years of experience be sufficient to allow waste canisters to be placed underground with negigible risk? The answer is one of judgement. Increasing the number of canister-years with heater experiments employing minimal instrumentation at several sites would increase the amount of our experience and could proceed parallel with those from the heavily-instrumented experiments. Prudence dictates that a portion of the repository itself be operated in a heater mode for a reasonable period of time, thereby constituting the next step in an increasing scale of experimentation.

Monitoring and parallel modeling should include at least the following:

a. Room stability during the operational phase of the respository - Do thermal stresses in the floor of excavations cause floor buckling or borehole collapse? Do stress readjustments around excavations result in a region of increased permeability?

5.8 Repository Design Considerations

To date a repository layout comprising parallel tunnels, connected perhaps at either end, and perhaps also at intervals between has been proposed. The parallel drift layout provides superior isolation for continuous construction, emplacement, and backfillings. Ventilation would be straightforward (a) until backfilling begins, when ducts become necessary and (b) if backfilling sections coincide with cross-drift access points. Long sections may require considerable traffic across waste-filled areas depending upon the type of backfill and mode of emplacement, and how closely backfill follows emplacement.

A room and pillar arrangement introduces additional isolation, stability, and stress concentration problems; but it reduces the size of intervals for ventilation and traffic over waste-filled areas. Isolation during continuous operations is less favorable due to multiple interconnections. Stability is decreased due to decrease in confinement of remaining rock and increase in exposure to surface damage. Stress levels are locally increased due to unfavorable geometry and probably overall due to extraction. Ventilation would require more complex control, but could be more easily provided during backfilling. Traffic over waste-filled areas would be slightly less dependent on the closeness of the backfill operations.

The significance of the above choice is probably greatest with respect to the possibility of stress induced cracking of the pillar area, which might significantly increase the permeability of the repository site. It might also affect deformability of the repository area rock mass. Depending upon design philosophy, this could be a major factor.

Input required for such analysis would include:

* Effect of excavation on local rock mass modulus
* Failure criterion for rock
* Room stability criterion
* Effect of shear displacement on permeability.

b. Effectiveness of backfill in preventing progressive increase in permeability around the excavation. Input needs include:

* Relationship between stress and permeability
* Thermomechanical properties of backfill
* Time dependent properties of jointed rock.

c. Repository integrity - Assuming an initially satisfactory hydraulic environment, assessment must be made as to the extent to which the hydraulic regime is modified by the repository. Questions to be answered include: Does the long-term thermo-mechanical cycle result in increased rock mass permeability? Will large-scale convection cells enhance radionuclide migration? Is there any possibility of large scale hydraulic fracturing? Necessary input includes:

* Stress/permeability relationship
* Conductivity/temperature/stress relationship
* Rock mass properties
* Failure criteria for jointed rock.

These examples represent only a few of the many that might be quoted.

Interactions between modeling, experimentation and design must persist throughout planning and early operational stages and lead to progressive confidence in the models.

5.9 Summary

Measurements of rock mass properties required during the life of the repository have been outlined for underground test facilities in typical crystalline and argillaceous rocks and for a site specific confirmatory test facility located at a potential repository site.

6. INSTRUMENTATION NEEDS FOR DETERMINING ROCK PROPERTIES

6.1 Introduction

Rock mechanics instrumentation has been developed in response to specific needs in civil and mining projects. Their apparent lack of sophistication in comparison to laboratory instrumentation is due to the requirement for robustness and serviceability in construction environments. The instruments generally require great care in calibration, operation, and interpretation of results, due both to the field environment and to the heterogeneity of the medium. Some instruments, particularly the more sophisticated ones, are highly operator dependent in terms of quality of results. There is a great need for comparison of results between different techniques, standardization of techniques, and improvements in function, especially at elevated temperatures.

There are several considerations of general importance:

a. The hostile thermal environment will create many problems, even with equipment that currently functions well at normal temperatures.

b. Cables and connectors should be standardized to allow efficiencies in development for environmental stresses and to allow multiple use of equipment.

c. Instruments should be designed if possible with standard overshot connection to improve retrievability.

d. Telemetry techniques should be developed further.

e. Long term reliability should be a major consideration in design.

f. Insofar as possible, instruments should be capable of being checked for function and calibration after emplacement.

The need for measuring rock properties and rock mass behavior, and instrumentation to make these measurements, should be examined with the goal of observing and predicting repository behavior clearly in mind. It may be adequate, perhaps more desirable, to measure some indirect integrated effect of the property rather than the property itself. Also, the accuracy and precision sought in various measurements should be consistent with the modelling assumption.

In the limited time available, we did not go into detail about the variety of instruments available. The discussion was organized in terms of basic quantities and how they are measured -- temperature, displacement (including strain), rock stress and fluid pressure and other measurement. The last section, 6.6, addresses the need for test facilities for development and calibration of instruments.

6.2 Temperature

Since much of the rock mass behavior and the repository performance is connected with thermo-mechanical behavior, accurate temperature measurement is critical during the experimental, commissioning, and monitoring phases. The technology in this regard is well developed; however, the cost of temperature sensing devices escalates considerably

with their accuracy. It will also be necessary to adapt these devices for underground and borehole use. It was estimated that temperatures should be measured to an accuracy of 0.1°C. This can be achieved with good thermocouples, but long term drift problems are significant.

While resistance devices can be accurate to 0.01°C their temperature range is limited, their cost is high and the complexity and bulk of the readout devices is great. The more sensitive devices are best suited to relative measurements. The difficulty of providing constant and reliable reference temperature precludes an extensive range, and thus presents a major problem in adaptation.

In order to minimize costs, a variety of types of temperature measuring devices should probably be used depending upon required accuracy at each point of measurement.

6.2.1 Device Selection

The objective here is to catalog enough information on temperature measuring devices to allow a selection that fulfills specific measurement requirements. Devices fall into several categories and sub-categories:

a. Thermocouples

If a thermocouple is adequate for the measurement, what type will best meet the requirement? For example, will a type K (Chromel-Alumel) thermocouple do the job or will a more expensive platinum-rhodium thermocouple be required? Since long term drift can amount to several degrees, keeping control specimens from the same melt may be of some use in correcting for drift.

b. RTD's (Resistance Temperature Devices)

This category includes any of the temperature measuring devices that change electrical resistance in a predictable manner as a function of temperature. This includes everything from "thermistors" (maximum temperature relatively low) to platinum thermometers. Generally this category is more accurate, stable, and expensive than the standard thermocouple and requires bulky and complex readout equipment.

c. Semiconductor Temperature Measuring Devices

This category is becoming worthy of consideration for approximate temperature measurement over a limited range where large output signals are required. Generally these devices take advantage of transistor base-emitter voltage drop variations as a function of temperature. Variations of $\pm 8^{\circ}C$ can occur from device to device. Single devices can be easily accurate to better than $\pm 1^{\circ}C$.

6.2.2 Accuracy, Stability, Reliability, and Packaging

Several characteristics and problem areas should be studied:

a. Short Term Device Stability

Some high temperature thermocouples exhibit an offset upon initial exposure to elevated temperatures that can be reduced by annealing before use. This may be true of other devices.

b. Long Term Drift and Contamination

Characteristics should be studied taking into consideration the specific influence of various geologic media. For example, what are the effects from contaminates in the rock and/or grouting material on the device, particularly if the integrity of the packaging or insulation should fail?

c. Effects of Electrical Leakage to Ground

How do we minimize the possibility of failure due to unpredicted ground loops, extraneous ground signals, self-potentials, tellurics, etc.?

d. Cross Talk (or Coupling) from Other Electrical Devices

Careful consideration in the total electrical and instrumentation system design must be given to coupling other instrumentation signals and/or higher power electrical equipment (e.g., heaters, lighting, etc.) into any of the instrumentation channels.

e. Packaging and Installation of Temperature Measuring Devices

Packaging of the device must be adequate to withstand any of the adverse effects (e.g., high pressures, corrosion, etc.) of the installation environment. Installation considerations should include the details of mounting and/or constraining the device in position and consider the effects of grouting, cementing or holding the measuring device in place with a mechanical device.

f. Associated Equipment

Careful consideration must be given to the complete temperature measurement system including the electronics used to condition the signal and to read out the temperature. Included are amplifiers, bridge circuits, ice point references, A/D converters, etc. One must consider the complexity, reliability, and accuracy of the total measuring configuration.

6.3 Displacement

Displacement is one of the most fundamental changes induced in the rock mass. Predictions of the magnitudes of these displacements by calculation show that they are, in general, small. It is highly impracticable to devise techniques for accurately measuring absolute displacements, so relative displacements are under consideration here. The relative displacements of interest fall into the range from 10^{-6} to 10^{-3} of the distance separating the points between which they are to be measured.

6.3.1 Mechanical Extensometers

Despite major advances in distance measuring techniques which have been made over the past few decades, displacement measurements in underground excavations are generally made using mechanical extensometers. Under the essentially isothermal conditions of many underground excavations, the principal limitations to the accuracy of mechanical extensometers are hysteresis, creep, and catenary effects in near-horizontal directions. Temperature changes, particularly those which involve temperature gradients along the length of an extensometer, introduce major complications. The effect of temperature has to be removed either by using rods made from materials with low coefficients of thermal expansion, such as Invar, or by correcting for thermal expansion, or both. In practice, the resolution of the best mechanical extensometer is of the order of 100 microns.

Invar and Super-Invar rod extensometers approach zero coefficient of thermal expansion over limited temperature ranges. In the case of standard Invar any practical zero coefficient of expansion

characteristics are exceeded after a maximum temperature of about 25°C. For Super-Invar this is extended up to the 100°C range. For temperatures greater than these, Invar thermal expansion is about the same as that of stainless steel. Any displacements measured in higher temperature fields must be compensated taking into account temperatures along the rod, and for displacement measurements good to 1 part in 10^6, Super-Invar must be temperature compensated even below 100°C. Thus present extensometers become difficult or impractical to use in high temperature fields, and extensive calibration and attention to environmental effects is an absolute necessity.

Over small baselengths, displacements can be measured with LVDT's or DCDT's to a high degree of accuracy. These devices have not been evaluated at elevated temperatures, and further work is essential.

6.3.2 Microwave and Optical Methods

In addition to displacement measuring methods using mechanical devices, microwave and optical methods can be used to a resoluton of 10^{-6} or better. There are at least three possible methods which should be explored in detail. Millimeter-wave radiofrequency-type interferometry using Fabry-Perot high-Q resonant cavity can be adapted for high-resolution displacement measurements. The second method, which uses the laser ranging principle, can be improved to allow generation and detection of sub-pico-second light pulses and the accurate measurement of the time of flight of a light pulse. Finally, an interferometry method, using continuous-wave laser radiation at two different wavelengths to allow for the atmospheric correction, can be adapted and improved for the 1 m - 100m range.

The technology exists for these methods. Development would be needed to adapt them to the specific borehole geometry and environmental conditons.

6.4 Stress

One of the most fundamental measurements required is that of the absolute state of stress in the rock, or, more particularly, the value of the minimum principal stress and the maximum effective stress difference. A variety of techniques for determining stresses in rock has been developed but the accuracy of each is questionable and the correlation of results from different techniques is not good. Accordingly, it is important that every effort be made to advance our understanding of the performance of limitations of existing techniques and to seek out and develop promising new ones.

Another important question is the heterogeneity of the state of stress throughout a rock mass. This issue can be approached from two different directons, either by endeavoring to obtain an average value, such as hydraulic fracturing tends to do, or to examine the variation from point to point. As the variations may be of consequence, attention should be given to the latter aspect. In this regard, the vertical component of the state of stress may be useful if it can be determined along the length of a vertical borehole. The value of this component should, on average, be equal to the stress generated by the weight of the overburden.

Hydraulic fracturing was discussed as being the only well-developed true stress measurement technique. The assumption involved in the

technique and its relative inaccuracy were considered the major drawbacks. Considerable research and development in this area is required.

Stress determination to within 100 psi is considered desirable for crystalline rocks, while even more precise measurements would be desirable for argillaceous rocks. One hundred psi approaches the limits of precision of our most precise indirect techniques (overcoring) under the best of conditions, and the accuracy is relatively unknown. USBM gauges have already been adapted for use up to 200°C. Research is needed for establishing true accuracy and reliability, and development is needed for reliability, improved accuracy, and use in borehole depths greater than 50-100 m.

Instruments such as the vibrating wire gage and flatjack (thin-cell) system need further evaluation in order to be quantitative tools for measuring absolute or temporal changes in stress.

6.5 Other Measurements

6.5.1 Fracture Aperture

Monitoring of fracture aperture in response to thermal loading was considered from the point of view of progressve increases in rock mass permeability. It was decided that change in fluid flow behavior was better handled as a bulk property, since flow paths in fractures are heterogeneous and probably do not occur as simple or uniform planar channels.

On the other hand, there will probably be a number of individually significant and definable structures at a given site which should be monitored due to their unique importance, both hydrologically and

for evaluation of mechanical rock mass response. The technology is straightforward, but specific instruments will have to be developed.

6.5.2 Acoustic Measurements

The acoustic cross hole technique can give a semi-quantitative picture of the fracture system and rock modulus between two boreholes. In situ measurements must be calibrated by using lab measurements on both unfractured and fractured samples under different temperatures, stress and hydrostatic conditions. The instruments for in situ untrasonic techniques need improvement and development, e.g., energy output for p- and s-wave transmitters to improve signal/noise ratio. Development of a multifrequency instrument would be advantageous for a better understanding of the behavior of acoustic signals in fractured rock. Tests and development of a multi-transmitter and receiver instrument should also be conducted.

6.6 Large Scale Testing Facility

An essential part of the development of new instruments involves testing them in rock under well-controlled and well-defined conditions of stress, strain, pore fluid pressure, and temperature. Such testing is reqired at all stages of development from initial embodiments of the concept through various prototypes to the final calibration of production versions.

It is very difficult to define conditions in the field and even more difficult to exercise any control over them. Accordingly, it is most desirable to have access to laboratory facilities sufficiently large to apply appropriate loads to rock specimens with dimensions of a meter or two.

Instrument development would be but one of the many important purposes which such a facility would serve. Size or scale is known to have a most significant effect on most geomechanical behavior. To bridge the gap between well-controlled and well-defined small-scale laboratory experiments and those done in the field, it is necessary to test the behavior of rock specimens with dimensions of a meter or two over ranges of stress, strain, pore fluid pressure and temperature at least as great as those expected to be encountered in any actual repository.

Some concern was expressed about the cost of constructing and operating such a facility. It is possible that this could be partially underwritten from other sources with overlapping areas of concern. It is also possible that much of this work could be handled with some modifications at various existing facilities, or with care and difficulty, in situ. There is no doubt that a large portion of this work is essential, however it is accomplished.

In addition to laboratory facilities, a field test facility is essential and should be developed (see Section 5.1).

7. SUMMARY OF RECOMMENDATIONS

Table 3 summarizes recommendations of this Panel.

7.1 Borehole Measurements

The higher priority items for borehole measurement methods are:

a. Develop sites with cored boreholes of varying depth and spacing, the sites to be located in rocks typical of desired repository rock types. Such boreholes would be used for

Table 3. Summary of In Situ Testing During Sequential Development of a Hypothetical Repository.

	Baseline (0 years)	Construction (1-10 years)	Emplacement (10-30 years)	1st phase storage (30-100 years)	(100+years)
	Underground Test Facility	Confirmation Test Facility			
Mechanical	Laboratory tests	Displacement closure	Backfill experiments	Temperature, displacement, stress	Temperature, displacement, stress
	Baseline models	Virgin stress state	(Retrievability)		
	Thermomechanical tests conducted to failure	Tests not conducted to failure			
	Canister-scale displacement	Temperature			
	Temperature	Same as in baseline underground test facility			
	Permeability Pore pressure				
	Elastic and time dependent properties				
Thermomechanical	Absolute stress; temporal change in stress				
Geological	Three dimensional representation of joints and fractures	Three dimensional structural representation of geology.			
Hydrological					
Radionuclide Transport					
Radiological					

1. developing, calibrating, testing, and operating the suite of slim-hole geophysical logging tools. Important here is improving our interpretive capability for the analysis of borehole logs.
2. an opportunity to test drilling and coring technologies.
3. testing cross-hole techniques.

b. Improve methods of measuring in situ state-of-stress.

c. Improve methods of delineating fracture characteristics, both in a single borehole and between boreholes.

d. Improve methods of measuring the pore space properties: permeability, porosity, surface area and chemical sorption.

7.2 Full Scale In Situ Testing

7.2.1 Recommendations

a. Establish confirmatory test installations under the anticipated in situ environment at potential repository sites where approprite could be conducted.

b. Develop and validate models capable of evaluating effects of thermomechanical phenomena with radionuclide transport.

7.2.2 Priorities

a. High Priority

1. Thermomechanical tests (e.g. "hot water test") in crystalline rock at a representative in situ environment on an excavation scale.
2. Conduct canister scale thermomechanical tests (heaters, etc.) in typical crystalline and argillaceous rocks.

3. Develop the tools and techniques to measure absolute stress and the change in stress with time.

b. Intermediate Priority

Evaluate the role of thermally induced fractures. After laboratory backfill development, conduct in situ experiments with appropriate boundary conditions. Conduct large scale flatjack tests to simulate in situ conditions. Develop methodology to assess fracture aperture, roughness, persistence and geometry.

0 0 1 0 4 9 0 5 7 5 8

FRACTURE HYDROLOGY

0 0 0 0 4 9 0 0 7 5 9

FRACTURE HYDROLOGY

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FRACTURE HYDROLOGY

1. INTRODUCTION

The Fracture Hydrology section of this Conference was considered by most participants to be the second in a series of workshops on the movement of fluids through largely impermeable rocks. The first such workshop was held in Austin, Texas, in January 1977 (Witherspoon, 1977) and was attended by many of the same people who participated in the GAIN Conference. The conference thus served as a forum for identifying the progress which had been made in the field since the Austin meeting.

A major recommendation of the Austin meeting was the use of existing underground mines for development of techniques for measuring the parameters that control fluid flow in fractured rock. A substantial amount of work has since been performed in this area, in the U.S. (Witherspoon, et al., 1978), in Canada (Raven and Gale, 1976) and in Europe, where the first major comprehensive undergrounnd thermo-mechanical and fracture hydrological studies in crystalline rocks have been initiated at the Stripa mine in Sweden (Witherspoon, et al., 1978; Witherspoon and Degerman, 1978).

Other recommendations of the Austin meeting included studies of stress-permeability relationships, the effect of scale on injection tests, groutability of fracture systems, improved techniques for identifying the hydrologic properties of fractured media, and the development of alternative monitoring systems for near field and far field effects of the repository. Subsequent work has been performed in most of these areas and was reported at the conference.

The discussions and recommendations of the Fracture Hydrology panel are reported in the following paragraphs. Five priority research areas were identified as follows:

- Factors Controlling Water Flux and Velocity. Since transport of radionuclides from a geologic repository to the biosphere will be through the groundwater, it is essential to develop techniques to accurately determine hydrologic parameters both near the repository and on a regional basis.
- Numerical modeling. Accurate numerical models must be available to determine regional flow patterns once the basic hydrologic data are available. It is through such models that critical factors such as contaminant travel times and discharge areas will ultimately be predicted.
- Comprehensive Site Studies in Mines and Undisturbed Rock Masses. A serious need exists for field facilities in which hydrological testing procedures can be developed under simulated repository conditions but without the constraints that currently exist regarding tests which affect the integrity of an actual repository site.
- Field Tests for Radionuclide Transport. The transport of radionuclides from a repository will depend upon the chemical and sorptive properties of the fractured rocks and the geometrical nature of the fracture system. Field testing techniques must be developed to provide required input for hydrologic transport models.

- Borehole, Shaft and Tunnel Sealing. The effective sealing of exploratory boreholes and access shafts and tunnels will be an absolute necessity for a geologic repository. Research on sealing materials and emplacement techniques is required and until an effective sealing technique can be demonstrated, the concept of geologic storage cannot be entirely validated.

2. FACTORS CONTROLLING WATER FLUX AND VELOCITY

2.1 Flow Laws

Accurate field identification of the factors controlling water flux and velocity in deep fractured reservoirs was considered to be one of the most important areas for research associated with nuclear waste disposal. Groundwater flow in both porous and fractured media occurs in a network of void spaces which penetrates the system. Flow in the system is generated by a hydraulic gradient (I), which can be defined as change in head per unit of distance in a given direction. The resistance to such flow is called the relative permeability (K) of the medium and is related to the discharge Q by the familiar Darcy equation:

$$Q = KIA \qquad (1)$$

where

Q = volumetric flow rate (L^3/T)

K = relative permeability (L/T)

I = hydraulic gradient (L/L)

A = cross section area (L^2)

Dividing both sides of the foregoing equation by the area A, an expression for apparent flow velocity V is obtained:

$$\frac{Q}{A} = V = K\ I \tag{2}$$

where

V = apparent flow velocity (L/T)

Each of the above terms has directional properties. Both velocity and gradient are vectors and the relative permeability is a tensor which varies in direction in response to changes in the physical properties of the void spaces. Equation (2) can thus be expressed in terms of a three-dimensional non-diagonalized tensor:

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \begin{bmatrix} I_x \\ I_x \\ I_z \end{bmatrix} \tag{3}$$

where the subscripts x, y and z indicate the orthogonal field coordinates. The x-component of velocity may, for example, be written:

$$V_x = K_{xx}\ I_x + K_{xy}\ I_y + K_{xz}\ I_z \tag{4}$$

where K_{xy} is, for example, the permeability to flow in the x-direction due to the component of gradient in the y-direction. If the orientation of the field coordinates coincides with the directions of principal permeabilities, the cross terms in the permeability tensor are reduced to zero and Equation (3) becomes:

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix} \begin{bmatrix} I_x \\ I_y \\ I_z \end{bmatrix} \tag{5}$$

where K_x, K_y, and K_z are the three principal permeabilities of the rock mass.

The true intergranular fluid velocity is generally computed for porous medium flow by dividing the apparent flow velocity by the porosity of the medium. Porosity is also used by the geochemist to estimate sorption effects. As discussed in the following paragraphs, however, estimates of velocity of sorption effects based upon porosity may be in error in a rock containing fractures with a wide range of apertures.

The primary factors governing water flux and velocity are discussed in the balance of this section and include fracture continuity, directional permeability, stress-permeability relationships, hydraulic gradient, and porosity. Research and equipment development needs are summarized following these discussions.

2.2 Permeability

Three major factors influencing permeability were considered basic areas of research need. These were, in order of importance, determining the directional permeability of fractured rock masses, determining the hydraulic continuity of fractures, and determining the effect of stress on an aperture. In the latter case, effects of thermal stress, tectonic and lithostatic stress, and shear stress and displacement should be noted.

2.2.1 Continuity

The ability to establish the statistical orientations and spacings of fractures is well established. Aperture can be estimated through borehole television, injection tests, or impression packers. What we cannot now evaluate is continuity, or the degree to which fractures continue in their own plane. To some extent this is a problem of aperture variation where aperture can equal zero. Continuity may, with aperture, be a major control on rock mass permeability. Some suggestions for evaluating continuity include:

- Investigations of rock mass in different tectonic settings to determine if tectonism affects continuity. This approach could include detailed geologic mapping of fracture systems as well as borehole tests;
- Studies of well yields in crystalline rock terrains to determine what trends exist;
- Evaluation of transient permeability tests on single fractures.

There is a need for large scale long term tests such as:

- Study of drainage around existing mines where the pressure distribution of fractures around the mine will depend on their degree of connection with the mine;
- Computer modeling studies in which the apertures of fractures or lengths of fractures can be varied at random, and the results used to design appropriate field tests.

2.2.2 Determining Directional Permeabilities of Fractured Rock Masses

In the vicinity of a repository site care must be taken to identify major potential flow conduits such as faults and shear zones in plutonic and metamorphic rocks, and sedimentary interbeds and rubble zones in volcanic and argillaceous rocks. Such features are generally found in conventional site exploration surveys. The rest of the rock mass where flow occurs in joints and smaller fractures may be highly anisotropic due to fracture spacing and orientation, aperture variation, in-situ stresses, and other causes. Such rock masses do not lend themselves to traditional hydrologic testing where anisotropy is taken into account only in a limited way. It is therefore important that repository exploration programs incorporate tests designed to evaluate anisotropy.

Five approaches to assessing anisotropy were discussed.

The first approach consists of using discrete fracture data to describe the rock mass in the form of a permeability tensor for an equivalent anisotropic continuum. This approach requires careful mapping of the fracture system, oriented core drilling approximately perpendicular to the principal fracture sets, detailed logging of the drill core in order to describe the geometry and characteristics of the fracture planes, detailed injection testing to determine effective fracture apertures, and the mathematical integration of these data into the form of a permeability tensor.

Regarding these techniques, TV camera logging provides a good check on fracture location, apparent aperture, and orientation, and can utilize oriented boreholes drilled either from the surface

or from underground. Careful drilling using triple-tube core barrels to enhance core recovery, and careful core orientation and logging are essential to the application of this approach. Characterization of the degree of fracture interconnection and its impact on fracture permeability should be incorporated into this approach.

Effective aperture is currently determined through constant head injection tests. Because of difficulties encountered in measuring low flow rates it is possible that the assessment of aperture in low permeability rock can be more easily effected through the use of transient tests. The theory behind such tests is fairly well documented and laboratory tests are underway to determine the correlation between permeability determined using steady state pressure flow rate relationships and the permeability determined using transient pressure data. Field tests of the pressure transient method are currently under way in Sweden using modified borehole assemblies. In such tests, where the displacement of very small volumes of water is concerned, there is definite need for onsite calibration.

The second approach, described by Louis and Pernot (1972), requires careful mapping of fracture orientations and the use of these data to calculate the predicted directional permeability axes for the rock mass. A central borehole, with four peripheral boreholes, is drilled parallel to each of the three principal permeability axes. Interpretation of multiple packer injection test results are based on fluid pressures measured in the four peripheral boreholes. This approach has been applied to only one area (Louis and Pernot, 1972) and thus there is a need for application to other areas.

The third approach consists of drilling orthogonal boreholes and testing the boreholes with increasing packer spacing. It is anticipated that with increasing packer spacing the permeability of each fracture set should approach a representative value. There was disagreement as to whether this approach would yield sufficient data to determine a permeability tensor. Thus there is need for additional theoretical work in this area.

A fourth approach is to combine results of injection testing with data derived from geophysical measurements to determine anisotropy. Since seismic velocity is dependent, in part, on the aperture and contact area of fractures, velocity anisotropy may reflect hydrologic anisotropy. Geophysical measurements could therefore be used to determine approximate principal axes of permeability and then borehole injection tests in holes normal to the principal planes would be used for quantitative evaluation.

In argillaceous rocks and basalts there are commonly higher permeability arenaceous zones. In those rocks vertical permeability in the aquitards may be studied by pump testing either by analysing leaky aquifier response of the drawdown or by using the ratio test (Neuman and Witherspoon, 1972) where the ratio of the vertical permeability of the aquitard to the permeability of the aquifier is determined from a pressure response in packed off portions of the aquitard.

The first approach is currently being applied to the Stripa site; existing borehole patterns at Stripa should allow use of Louis and Pernot's methods or geophysically related methods. Pump test

methods should be tried at Hanford and argillaceous sites under consideration. In addition to work at Stripa and on nuclear reservations, it was agreed that testing in an area with a simple fracture system and good surface exposure would greatly increase confidence in these methods.

2.2.3 Effect of Stress on Fracture Permeability

Stress can affect the effective aperture of a fracture and therefore have a large effect on the permeability of rock. Decrease in permeability with depth is often considered stress related, and such a decrease has been shown by Davis and Turk (1964) and Snow (1968). There has been some discussion of whether this decrease is due to decrease in fracture density at nearly constant aperture or decrease in aperture at constant spacing. Since velocity is a function of aperture squared and is independent of spacing (Maini and Hocking, 1978), this question is critical indeed. Studies by Raven and Gale (1976) and Kendorski and Mahtab (1976) suggest aperture decreases while fracture geometry remains fixed; however, work done by Swedish investigators in granite shows that fractures with significant apertures do persist to depth but with smaller frequency so that the overall permeability of one well tested was as low as 10^{-10} cm/s.

To some extent this effect can be studied through laboratory fracture permeability tests. However, caution was noted in conducting such tests by several participants. One participant referred to experimental work by Maini and others that suggested increases in fracture permeability with shear displacement, an affect that might

be especially important in fracture behavior near the repository excavation and in the area of thermal loading.

Experimental work at Berkeley by Gale, Amick, and Witherspoon on the effect of normal stress on fracture permeability showed that core size has a major effect on the results (cores 152 mm and 914 mm in diameter were tested). Permeability of induced tension fractures varied with core size over an order of magnitude under the same loading conditions. The higher permeability found in the larger cores was attributed to a decrease in the percent contact area over the fracture surface, thus allowing flow channels to remain open (Figure 7). It was felt that increasing the core size from small diameters to large would result in increasing permeabilities until the core diameter reached a size representative of field conditions (region B in Figure 7).

The implications of these fracture flow studies on rock of different dimensions are important. If these first results with an ultralarge core are indicative of the true flow behavior in a fracture under stress, it is apparent that further work on the question of sample size is needed.

Another aspect of the stress-permeability question for fractures is the effect of thermal loading on fracture aperture. The need was discussed for coupled heat-stress-flow models but experimental work is also required. Recent laboratory and field work (Lundstrom and Stille, 1978; Summers, et al., 1978) indicate decrease in permeability with temperature. These experiments are limited in number, however, and more work needs to be done, especially in terms of in situ tests where the aperture changes can be isolated. One possible test might

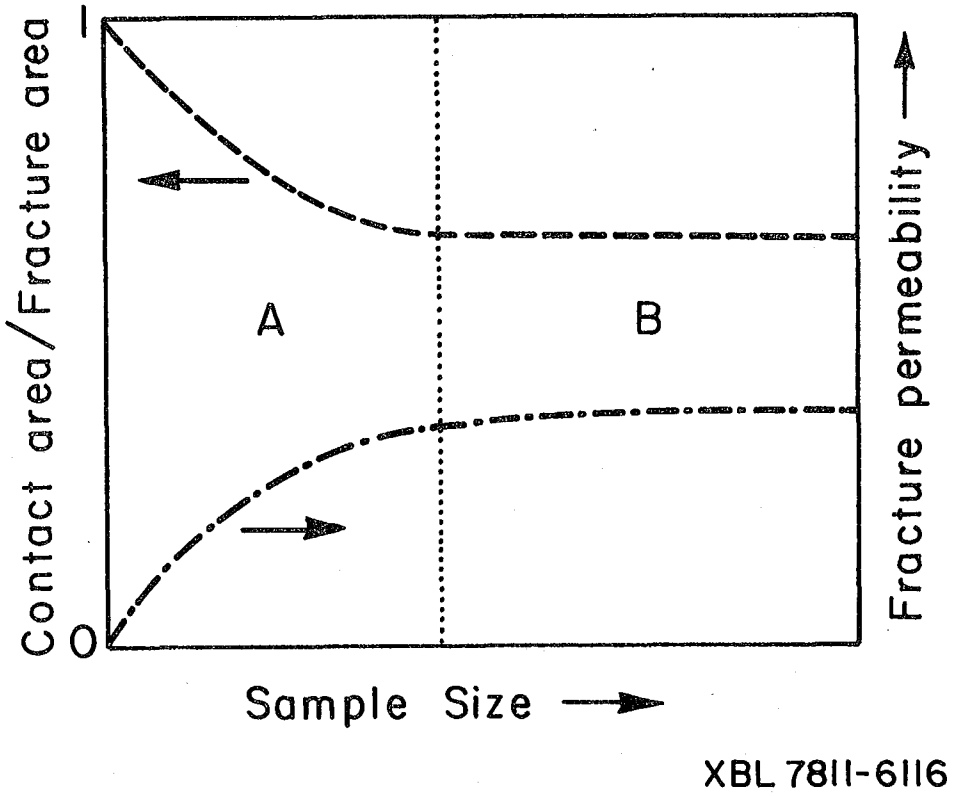

Fig. 7. Effect of contact area on fracture permeability at a given stress level for various sample sizes.

Region A -- schematic representation of small samples shows size-dependent effects on fracture permeability, possibly related to contact area in the fracture.

Region B -- schematic representation for larger sample sizes shows fracture permeability independent of size of sample tested.

be a rerunning of the Pratt block experiment (Pratt, et al., 1977) with heaters. As mentioned in the previous paragraph, scale effects must be considered here as well.

2.3 Pressure Gradient

As Darcy's law clearly states, fluid flow is dependent on pressure gradient. Measurement of pressure, or hydraulic potential, provides basic information for determining direction of groundwater transport in three dimensions. Such measurements provide, as well, qualitative insight into the hydrologic role of such geologic features as faults, folds, and fracture systems.

Although the pressure gradient is clearly of equal importance to permeability in determining water flux and velocity, the characterization of gradient was felt to be relatively well understood and received little discussion during the conference.

The importance of pressure monitoring in the vicinity of a repository site was emphasized, both during repository construction and after waste emplacement. Monitoring before and during construction will provide an excellent check of earlier permeability estimates, because the excavated area will act as a large well into which drainage will occur. Monitoring will also provide a means of verifying predictive models. Such a test would provide valuable indications of permeability and porosity for large masses of rock.

Long term pressure monitoring will be required to assure that changes in gradient, which could significantly alter flow velocities and containment times, do not occur unnoticed. Significant changes in gradient are entirely possible and have occurred in geologic time

with changes in such things as climate, sea level, and elevations of riverbeds. The activities of man can also induce significant changes in hydraulic potential such as by well pumping, irrigation with imported water, and reservoir construction. Long term monitoring should ideally be continued as long as the escape of waste materials would pose a safety hazard.

Recommendations were made regarding the need for improved downhole pressure measurement equipment which would provide for pressure pulse control and for detection of packer leaks, both in the packer-to-rock seal and within the packer fluid injection system. Reliable and durable equipment for long term monitoring at multiple intervals within a single well is also needed.

2.4 Porosity

Data on the porosity of a fluid-conducting medium provide information regarding the voids in which the fluid moves. This information is required for two primary purposes: to estimate the true fluid velocity for travel time computations and to estimate the void surface area for geochemical reactions.

The velocity calculated using the basic flow equations is an apparent velocity and not the true intergranular fluid velocity. The average true velocity is equal to the volumetric flow rate divided by the effective cross-sectional area of the pores and fractures, rather than the gross area of pores, fractures and rock matrix. In a random and relatively uniform porous medium, the average true velocity is essentially equal to the apparent velocity divided by effective porosity, defined as the ratio of interconnected pore volume to gross volume.

This simplified relationship breaks down, however, in a fractured medium where void spaces occur in the form of open fractures which are often highly irregular in size. In considering a volume of rock containing ten fractures of 10 μ aperture and one fracture of 100 μ aperture, the true velocity in the single large fracture will be 100 times the velocity in the small fracture because velocity is a function of fracture aperture squared. Dividing the total flux per unit area by the total porosity would therefore give an erroneously low value for velocity. It thus becomes very important when identifying true flow rates in a fractured medium to consider fracture apertures rather than gross porosity data.

The participants concluded that no effective means now exist for directly measuring either total or effective porosity. Porosity may be estimated from tracer tests by measuring true fluid velocities, or from geophysical tests by measuring rock mass density, conductivity, or water content. The tracer test provides the best measure of effective porosity, but even then assumptions may have to be made regarding the fluid flow path. In view of the problems that can arise in estimating porosity and in estimating true velocity from effective porosity in a system of irregular sized fractures, it may be better to consider a procedure which involves the direct measurement of fracture apertures.

Effective fracture apertures may be computed from permeability tests on single fractures by assuming the parallel plate model. If enough measurements are made on fractures of different aperture and orientation, a statistical model of the fracture network may be compiled

from which the probability of encountering any given set of orientations and apertures may be determined. Knowing hydraulic gradients, true velocities and travel times may be computed with a known probability of occurrence.

In order to build a complete fracture network model, data on fracture continuity must also be available. Very little information on this important parameter now exists, although, as previously mentioned, permeability tests on individual fractures hold promise to provide some information on this subject.

The importance of porosity on radionuclide sorption was discussed. Sorption is dependent on water flux and velocity and on fracture surface area. Flux and velocity are controlled by fracture aperture, and surface area is controlled by fracture density. Extending the foregoing arguments, it is evident that both surface area and aperture are poorly related to porosity. The alternative approach involving direct measurement of fracture aperture and fracture density was considered to be a possible solution, depending upon the needs of the geochemist.

It was recommended that tracer testing equipment and techniques be further developed using multiple well systems, and that statistical studies of the parameters governing fracture geometry be pursued. Refinement of geophysical methods would also be desireable, but this was not considered to be within the purview of the hydrology section.

2.5 Research and Equipment Development Needs

The major research needs for determining water flux and velocity are summarized below.

2.5.1 Permeability

The methods discussed for determining anisotropic permeability should not only be applied to one specific site but to other locations in different lithologic and tectonic settings. The equipment needs associated with this work mainly involves tools for better defining fracture geometry, specifically:

- Improved borehole TV cameras
- More use of impression packers
- More extensive use of triple tube split inner barrel coring equipment
- Review of existing borehole survey equipment for reliability and accuracy.

It was recommended that 76 mm be adopted as a standard borehole size.

For rock of very low permeability constant head tests will prove inadequate; hence equipment for transient (pulse) tests should be developed.

Tests to determine continuity of fracture systems will be essential and may take the form of large scale tests around underground openings, cross hole pulse or tracer tests, or modeling studies.

Psychrometric systems for measuring humidity in controlled ventilation tests in mines need to be developed.

Laboratory investigations of fracture permeability should include tests for the effects of temperature and an investigation of the effect of sample size on test results.

2.5.2 Pressure Gradient

Improved equipment and emplacement procedures are needed to study long term pressure trends and to monitor potential repository sites.

2.5.3 Porosity

Research is needed to investigate methods for determining the effective porosity of fractured rocks, especially in the context of defining an "equivalent porous medium" for modeling.

There is a need to develop tools for tracer tests including downhole tracer detection, downhole gas chromatography, and a downhole tritium probe.

3. NUMERICAL MODELING FOR INTERPRETATION AND PREDICTION

3.1 Introduction

Numerical models for hydrology have three major uses in geological disposal of nuclear waste. The first use of models will be in examining the regional groundwater flow system at a potential repository site. These models should identify flow paths and flow velocities througout the area of interest and identify the location(s) in the flow system which offer maximum flow times to the biosphere. The second use of models will be to assess the effect that building and loading a repository will have on the groundwater system. These include the long and short term, near and far field effects of creating the mine and shafts, heat generation, and projected radionuclide release. The final use of models is in assessment of the impact of events and situations which cannot be predicted accurately such as geologic processes, failure of a borehole plug, changes in hydraulic gradient, existence of a large unmapped fracture, catastrophic events, and accidental

intrusion by man. These possibilities can be examined either by adjusting the model parameters and boundary conditions or by incorporating statistical methods into the analysis.

Models currently available for the first two uses, i.e., simulation of flow, transport, and stress, take several approaches. Discrete models treat flow in discretely described individual fractures; continuum models treat flow in true porous media or in groups of fractures represented as an equivalent porous medium. Where significant flow occurs both in the rock matrix and in the fractures, hybrid continuum discrete models or double-porosity continuum models can be applied. There is general agreement among modelers, as well as field investigators, that more than one approach is required for evaluating the safety of a geologic repository.

In the analysis of regional groundwater flow, continuum models are expected to be used. The analysis will be on a large scale and it will be extremely difficult to represent each individual fracture. An exception to this will be caused by the presence of large through going joints or faults. Documented or hypothesized existence of these features may necessitate the use of hybrid models.

Assessment of the effect of the repository will require increased modeling capacity. Near field and short term effects will most certainly have to take into account individual fractures. Furthermore, the coupled effects of expected heat production, stress, radioactive decay, rock-water-waste interaction and hydraulic mixing should be included in the analysis.

For analysis of the impact of uncertain events and situations three types of approaches can be utilized. The first and most straightforward approach is to develop a scenario for "worst case" analysis such as assuming a catastrophic flood. By changing the appropriate boundary conditions and/or parameters in the existing models the effects of these scenarios can be evaluated. The second approach (the Monte Carlo approach) is to determine the statistical properties of the values used for parameters, boundary and initial conditions. The actual values used in the models are then randomly selected and a large number of solutions are generated. The statistical properties of the population of solutions are then determined. The last approach is to incorporate uncertainty directly into the calculational model. In this method the solution might be in the form of a mean value plus a standard deviation.

The rest of this section will be concerned with assessment of the state of the art and research and validation needs in modeling.

3.2 State-of-the-Art

Currently many models have been developed which cover some but not all phenomena associated with siting, construction, short-term near-field, and long-term far-field aspects of a repository. Even though the state-of-the-art in modelling is well developed, considerable work remains to be done on models for fractured crystalline and argillaceous rocks. To develop the necessary models researchers must formulate basic theory, conduct laboratory and field tests, incorporate the research results into mathematical models, and verify these models by comparison of simulated results with the results of field tests

and demonstrations. Some of the existing models and their capabilities are listed below. The list should be considered as representative of the state-of-the-art rather than exhaustive:

3.2.1 Models for Regional Flow Analysis

a) KBS model: 3 D flow

(Note: KBS, please describe this model)

b) Double Porosity Model (J. Duguid)

2 D flow

(Note: J. Duguid, please describe this model)

c) Trust (LBL, T. N. Narasimhan)

- 3 D water saturated and unsaturated porous system and/or discrete fractures.
- Solves fluid convection by integrated finite difference method
- Calculates consolidation using 1-D theory of Terzaghi
- Can handle: Spatial variations of aquifier properties; pressure dependent permeability (unsaturated flow); different boundary conditions.

3.2.2 Models for Analysis of the Repository Effects on the Ground Water System

a) CCC (LBL, M. Lippmann)

- 3 D water saturated porous systems and/or discrete fractures
- Solves fluid and heat conduction and convection simultaneously by integrated finite difference method.
- Calculates consolidation using 1-D theory of Terzaghi

- Can handle: Spatial variations of aquifier properties; temperature and pressure dependence of rock and fluid properties; different boundary conditions; gravitation effects

b) Princeton model (G. Pinder)

- 2 D flow
- Mass transport
- Energy transport

c) Porfrc (LBL, M. Ayatohalli)

First version:

- Models porous fractured media
- Used for analysis of stress and fluid flow in fractured rock masses
- Restricted to two dimensional and axisymmetric single phase saturated media.
- Solves for displacements and fluid pressure simultaneously using finite element method.
- Can handle: Steady state flow under static equilibrium; nonsteady state flow under (quasi-) static equilbrium; regions with different material types (up to 12); linearly elastic isotropic solids; fractures with nonlinear structural properties; initial stresses and boundary conditions; constant pressure and(or) constant flux boundaries; fractured rock masses as well as unfractured continuua; rigid systems as well as deformable ones; gravity flow and body loads.

Second version: (yet to be validated)

- Models two dimensional fractured rock masses.
- Used for analysis of thermomechanical stresses in fractured media.
- Solves for temperatures analytically and computes displacements and stresses due to temperature change by finite element method.
- Can handle: initial stresses; boundary loads; body forces.
- Restricted to: transient heat flow from constant line sources; isotropic and linearly elastic solids; heat flow by conduction only.

d) FAULT (U.C. Berkeley, Noorishad, J. Gale, R. L. Taylor)

- 2 D finite element program
- Can handle: coupled stress and fluid flow; flow problems in fractured media with stick-slip failure conditions.

e) KBS: 2 D fracture flow

(Note: KBS, please describe this model)

f) NOMOHR(?) (RESPEC)

- 2 D coupled(?) stress-fluid (FE) code
- Flow restricted to steady state
- Can handle: 2 D coupled stress-fluid in discrete fractured media
- Limited to small problems

g) GWTHERM (Univ. of Minnesota)

- 2 D coupled heat and fluid flow
- Porous medium
- Uses IFD method with ADI time integration

h) Programs run in tandem:

Certain features of coupling can be achieved by feeding the stress-dependent permeability back into the heat and fluid flow program.

Examples:

i. CCC + SAP IV (LBL)

SAP IV is a 3D linear, FE stress code that can handle thermal stresses with temperature dependent elastic properties.

ii. CCC + BMINES (Agbabian Assoc. for USBM)

BMINES is a 3D FE code for underground structure modeling that can handle: 1,2,3D solid continuum stress analysis with 2D fractures; both linear and nonlinear analysis.

iii. GWTHERM + FE Stress Code (Univ. of Minnesota and Dames and Moore)

GWTHERM does coupled heat and fluid flow in 2D porous media.

FE stress code does thermo-mechanical response of joints in 2D.

3.2.3 Modeling of Uncertainty

NOTE TO REVIEWERS: Please note how your models handle uncertainty.

The simulation of subsurface phenomena, such as groundwater flow, oil reservoir performance, and mass and energy transport are fraught with uncertainty. The sources of uncertainty are many but are concentrated in the following three areas: (1) the form of the governing physical

equations; (2) the form and evaluation of initial and boundary conditions, sources and sinks; and (3) the functional form of the equation parameters, i.e., their distribution and magnitude.

The form of the governing equations for many problems has been known for some time and withstood the test of time with only minor modification. This is not necessarily true for some problems relevant to radioactive waste transport. The equations describing multiphase energy transport are still undergoing scientific scrutiny and the governing equations for transport in fractured media are certainly not well understood. For porous media transport, however, the uncertainty in the form of the governing equation is probably less of a problem than the remaining two sources.

The importance of uncertainty in the initial and boundary conditions and sources and sinks is very much problem dependent. In the case of long simulation intervals the initial conditions play a decreasingly important role until, under steady state conditions, they play no role at all. However, as the simulation approaches steady state, the boundary conditions, sources, and sinks largely determine the form of the solution. The opposite situation holds for short term simulations: initial conditions are very important while boundary conditions are very data density dependent; that is, we can improve our estimates of these relationships provided we are prepared to pay the price both economically and in terms of project delay.

Parameter uncertainty is particularly interesting; its source is not so much due to measurement inaccuracy, as is the case in typical experimental situations, but rather to the method employed to extract

the parameter from the data. All hydrologic parameters of importance in the radioactive waste problem are determined indirectly. In other words, the inverse problems require a "correct" but "simple" model of the system under consideration. Often the conditions "correct" and "simple" are incompatible or the degree of complexity of the system is unknown. Whatever the case may be there is normally significant uncertainty in backing out hydrologic parameters given excellent field measurements.

Pinder (personal communication, 1978) has addressed the impact of parameter uncertainty on solution uncertainty. From parameter estimates provided by competent hydrologists he generated probability distributions for the velocity and dispersivity coefficients of the transport equation. Simulations over many thousands of years yield very interesting results and suggest that the governing equations tend to damp uncertainty as time elapses. If we assume the coefficient of variation is a suitable measure of uncertainty, input parameter uncertainty of several hundred percent may generate solution uncertainties of only a few percent. The magnitude and importance of the output uncertainty depends, of course, on the concentration level with which one is concerned. Pinder has conducted a number of potential numerical experiments and this general observation appears consistent.

The problem at hand becomes one of minimizing the uncertainty in input information at reasonable cost. Pinder is currently investigating, with some degree of success, the formal combination of objective and subjective field information. It seems reasonable to employ to the maximum degree possible the insight, gained through experience, of

the field hydrologist while at the same time making full use of available field data.

In the past we have largely ignored parameter uncertainty. In general a limited sensitivity analysis was considered adequate for most problems. Radioactive waste transport, however, is unlike other subsurface simulations. The uncertainty is very great because of the lack of data and the scope, in time and space, of the problem. The importance of solution uncertainty, on the other hand, is profound because of the impact of radionuclides on the biosphere. It appears that radioactive waste management is a problem not only with our best estimates of contaminant migration but also the confidence with which we make these forecasts.

3.3 Research Needs

Research needs exist for all three categories of model use.

3.3.1 Regional Flow Models

Codes for analyzing regional flow are very well developed. Parameters needed for input into these models are, however, extremely difficult to obtain. Two major methods can be used to identify these parameters. The first approach is to synthesize parameters from the interpretation of field data. In the case of permeability this can require careful mapping of the fracture system, drilling of boreholes approximately perpendicular to the principal fracture sets, oriented core drilling, and detailed logging of the drill core in order to describe the geometry. Detailed injection testing is used to determine effective aperture, and the mathematical integration of these data into the form of a permeability tensor is then performed. Numerical

analysis can also be useful in comparing the synthesized parameters with the results of large scale field tests and with regional flow data.

A crucial feature of this approach is identification of the size of a representative elementary volume (REV). Continuum modeling is based on being able to assign representative values to parameters for a finite volume. Bear (1972) has defined the size of a REV (Figure 8). If a test is performed on a volume smaller than the REV, the effect of adding a small volume to the test volume will have a significant effect on the value of the parameter measured. This smaller-volume range is the domain of discrete fracture effects. The volume is representative of the larger system when small increases in the test volume have no significant effect on the value of the parameters. This larger-volume range is the domain of porous media or equivalent porous media effects. If the REV cannot be defined, the continuum models cannot be directly applied. Models can be used to examine theoretical fracture systems and determine their REV.

The second method of parameter identification is solution of the inverse problem. The parameters are deduced from the response of the groundwater flow system to perturbation. Even though use of mathematical models to identify parameters by solution of the inverse problem is well advanced, more work is required to gain confidence that appropriate and realistic parameters have been selected.

In summary, 1) models should be used to design simple tests to determine the size of the REV in the field, and 2) there is a need

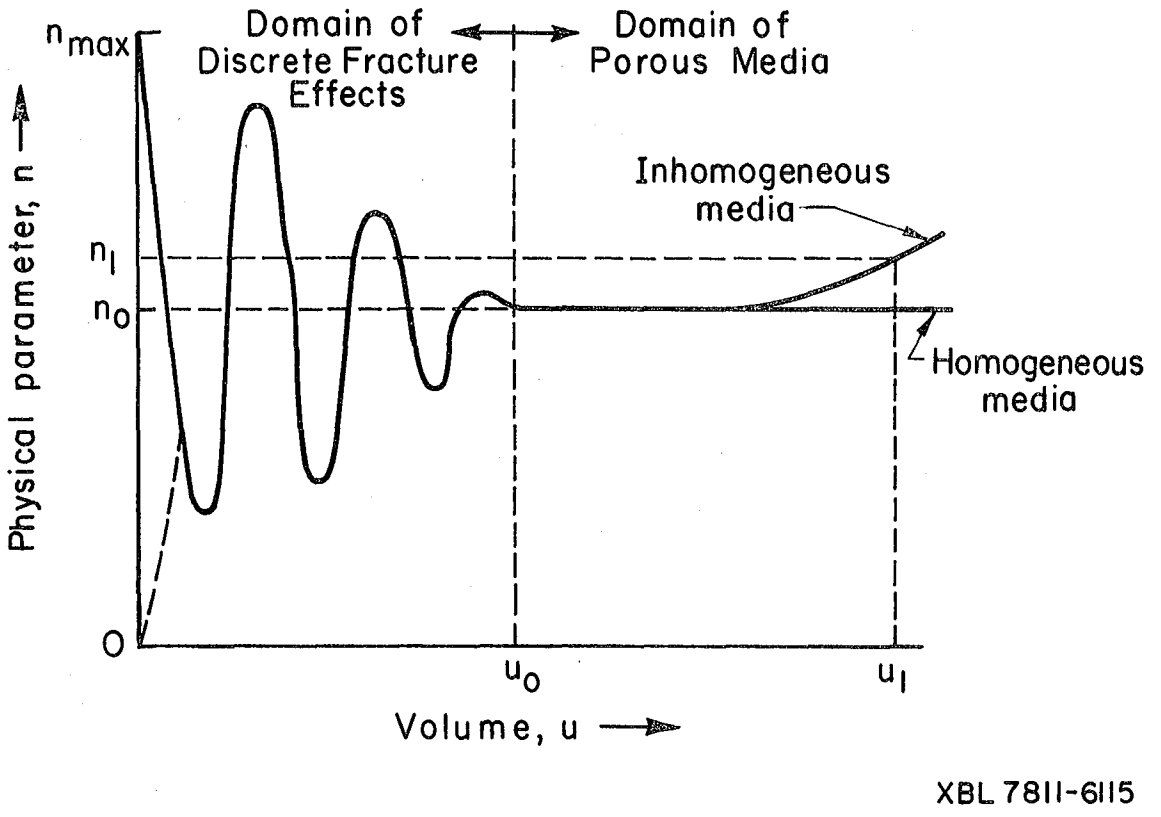

Fig. 8. Definition of a representative elementary volume (after Bear, 1972).

to define continuum properties from borehole data and to relate borehole data to the solution of the inverse problem.

3.3.2 Effect of the Repository

Models should continue to be used for investigation of the coupling terms between flow-stress-temperature equations. If laboratory or field tests can be developed to evaluate these coupling terms, they should be conducted in parallel with model development. To date a completely coupled three-dimensional model of temperature, stress, and flow has not been validated. The consensus of this panel is that work is needed on formulation of the governing sets of equations. It is foreseen that this model will be used to investigate the magnitudes of coupling terms between equations that have been previously modeled as uncoupled sets.

There is strong evidence that sorption and chemical reactions in fracture systems should be incorporated in the models in terms of fracture surface area, but currently existing models are not yet satisfactory. Simple sorption, in terms of bulk rock properties, can be easily incorporated into the existing continuum models; however more work is necessary to analyze sorption in terms of fracture surface area. Incorporation of chemical reactions awaits definition of these reactions through developments in geochemistry.

Hydraulic mixing or dispersion phenomena are processes by which the concentration of a solute decreases as flow proceeds. There are two mechanisms which accomplish this dilution. The first, tortuosity of flow path, causes dilution by spreading particles out relative to each other. This process occurs in the microscopic scale (within

individual pores or fractures), on the macroscopic scale (within fracture networks), and on the megascopic scale (equivalent porous medium). The second mechanism is molecular diffusion. Molecular diffusion enhances mixing by allowing solute particles to change flow paths. Molecular diffusion is usually only important on the microscopic scale.

The physical phenomena of hydraulic mixing are often described in a lumped mathematical parameter, the dispersion coefficient, which is constructed by analogy to Fick's diffusion coefficient. The dispersion coefficient describes the rate of spreading or dilution along a flow path and is a function of velocity. To accurately represent the physical situation, the dispersion coefficient must describe the effect of tortuosity on a scale smaller than the scale on which the flow path itself is described. For example, if in a fractured rock the flow paths are described in an equivalent porous medium, i.e., megascopic scale, then a meaningful dispersion coefficient will lump the effects of tortuous flow within the network of individual fractures. However, if the flow is described through discrete fractures, then a meaningful dispersion coefficient will describe the tortuosity of flow due to contact area and asperities in the fracture planes.

The problem arises that we can measure a dispersion coefficient in the field but if the inhomogeneties causing tortuosity of flow are not normally distributed throughout the volume tested, the concept of dispersion as a lumped parameter is inaccurate (Schwartz, 1977). A better way to understand mixing phenomena is to describe all inhomogeneities and therefore the flow paths in sufficient detail. Mixing due to flow path tortuosity is the fundamental process which

needs to be understood. Dispersion as it is currently defined and used may not be the best way to handle this effect.

On the basin-wide scale of a repository site analysis the mixing phenomena on the microscopic scale are of little interest. On the macroscopic scale this effect represents a dilution which can serve as a factor of safety in the analysis. On the megascopic scale, it will be important to understand and predict the process accurately by defining sufficiently detailed flow paths. Mixing on the microscopic scale can be measured with a sample in the laboratory or in a single fracture in a borehole. The megascopic scale can be analyzed fairly well with currently modeling tools but requires that parameters be assigned to the flow media on a macroscopic scale. Therefore the problem of understanding megascopic mixing is really the problem of parameter identification discussed earlier. Macroscopic scale mixing is the most difficult to analyze. Since on a basin-wide scale mixing is less important to dilution on the macroscopic scale than on the megascopic scale, macroscopic mixing has been placed low on the priority list for model development.

The effect of fracture initiation and propagation on the repository should be incorporated into models as this effect becomes understood.

3.3.3 Uncertain Events and Situations

The analysis of worst case scenarios will be no more complicated to modelers than the analyses required to understand the expected effects of the repository. The previously used models will be simply adjusted to the specific scenario and the results assessed.

The Monte Carlo approach has been successful in simple problems, but its application to complex flow systems would require an extremely large number of calculations.

The third approach of incorporating uncertainty directly into the calculational model represents a very difficult conceptual problem. Only simple problems have been attacked; however, this approach shows promise and is deserving of more research.

3.4 Priorities in Developing Models

Table 4 gives priorities of research need in developing models.

3.5 Model Validation

Existing models have not yet been sufficiently validated for fractured media. If these models and others that are under development are to be used for repository safety assessments, adequate model validation can only be carried out in conjunction with field testing and the following field tests are suggested:

a. Packer test with variable spacing in vertical and horizontal boreholes (determination of the REV);

b. Mine ventilation test (similar to that to be conducted at Stripa) to verify equivalent porous media permeability of fractured rock mass;

c. Packer test in three mutually orthogonal boreholes (pressure pulse test with observation wells) to determine the permeability tensor;

d. In situ heater tests (thermo-mechanical-hydrological data collected);

Table 4. Priorities of Modeling Research

Priority	Research Need
I	Parameter identification using models and theoretical determination of the REV.
II	Using models combined with field and laboratory tests to investigate coupling terms between stress, flow and temperature equations.
	Incorporation of sorption and chemical reactions in transport models.
III	Completion of coupled 3D stress-flow-temperature models.
	Models incorporating parameter uncertainty.
IV	Modeling of hydraulic mixing or dispersion (on a macroscopic scale).
V	Solution of the inverse problem for transport.
	Modeling of fracture formation and propagation.

e. Full scale repository demonstration facility complete with radioactive waste. This type of testing is being conducted for unfractured media using project Salt Vault data.

The conclusions drawn at the workshop were that modeling capabilities are still ahead of data-gathering capabilities. It was also the consensus that validation of models will remain in doubt until long term (on the order of 5 years) and large scale (on the order of 100 m) field tests and demonstrations have been conducted and compared with simulation results. Many of these tests for validation of flow models are relatively inexpensive and simple to conduct when compared to thermo-mechanical tests. Large-scale thermo-mechanical validation demonstrations must be performed in the repository itself; however, much confidence will be gained from models by comparing simulated and measured results from heater tests.

4. COMPREHENSIVE TEST FACILITIES

4.1 Need for Large Scale In Situ Tests

The in situ studies currently underway in several countries (Canada, Sweden, U.K., and U.S.A.) will yield much essential data for repository design. There may be a danger, however, in using results from a test at one site to predict behavior of another site with a different lithologic setting and tectonic history.

Tectonic history affects the hydrology of fractured rock in the following ways:

- It controls the orientation, spacing, and type of fractures present.

- Current stress state affects changes in fracture aperture with depth and the response of fractures to other loads such as those due to temperature or excavation.

The lithology also affects the repository site in terms of:

- Physical properties - deformation modes, elastic constants, thermal conductivity, anisotropy and inhomogeneity.
- Fracture types - e.g., cooling joints in volcanic rocks, foliation related joints in metamorphic rocks, and bedding joints in stratified rocks.
- Nature of fracture fillings, coatings, and degree of healing of fractures.

Newly planned in situ tests should endeavor, where possible, to work in geologic and tectonic settings different from previous experiments; similarly, application of results from one test site to another should be done with care.

Some of the variables to be investigated in any new site study are: fracture aperture changes with stress; anisotropy and continuity of the fracture system; effect of heat in generating new fractures or changing apertures of existing fractures; and geochemical characterization of the groundwater to determine age, flow system evolution, and effect of temperature on water chemistry.

Change in fracture aperture with stress is a function of the mechanical properties both of the rock and fracture fillings, and of the existing in situ stress field, which is a combination of the lithostatic and tectonic stress. It is of particular significance in considering changes in fracture aperture with depth. Experimental

work should include laboratory tests on flow in large fractured rock samples, in situ tests on isolated fractured blocks of rock (Pratt, et al., 1977) and injection tests on fractures over a large range of depths.

Anisotropy and continuity also are affected by lithology and tectonic history. Research into these effects should focus on surface and subsurface characterization of fracture systems in an attempt to answer such questions as the persistence of surface fractures, shear zones, and air photo linears with depth. An important question is whether or not a potential repository can be successfully characterized by surface investigations alone, thus limiting the danger of leakage of waste through poorly sealed exploratory holes.

Continuity studies should consist of detailed geologic mapping of fracture systems, cross hole hydrologic tests, and finally large scale tests which affect a large enough volume of rock in order to assure that no major fracture flowpath is being overlooked. These hydrologic tests should include tracer tests and large scale studies of the water pressure distributions about mines or other underground openings that have been open and pumped for long periods of time. The distance from the opening affected by dewatering should be a function of the permeability and continuity of fractures.

The effects of temperature on fracture systems include changes in aperture of existing fractures as well as generation of new fractures or extension of existing ones. Much of this work has been discussed by the Rock Properties panel of this symposium.

Geochemical characterization in terms of waste-rock interaction is discussed in the Geochemistry section. For hydrologic purposes, geochemical data provide velocity estimates based on age dates and, under some circumstances, indicate direction of flow if specific chemical constituents can be traced to a particular source.

4.2 Comprehensive Site Studies in Undisturbed Rock Masses

The Fracture Hydrology panel felt there was need to conduct in situ tests of the sort outlined above both in existing underground openings, such as mines, and in virgin sites.

The chief advantage of mines is the availability of underground access for minimum expense. The lead time associated with initiating a study in an existing mine can be less than a year, as the Stripa project has shown. Furthermore, studies of mine drainage can provide continuity and permeability data on a large scale which few tests can duplicate.

Mines have several distinct disadvantages, which include perturbation of the rock mass from mining activities and anomalous or unusual geologic conditions. The latter caused the mineral deposit to be concentrated in the particular site and, therefore, the unusual conditions of the deposit itself.

Site studies in mines should therefore be complemented with a test facility in a virgin state. The location for this latter site should be in an area of minimal disturbance (both thermo-mechanical and piezometric) and in a geologic and hydrologic environment similar to that of potential repository sites. The research activities at

such a test facility should span the full range of repository construction and operation from the exploration phase through the sealing and decommissioning.

Underground rooms for experimentation should be constructed at repository depths if funding allows. It is important, however, that the test site be designated for experimental work only so that experimentation that might impair repository integrity can be undertaken.

Exploration phase research would include:

- Testing of drilling methods for minimization of piezometric and geochemical disturbance.
- Extrapolation of surface fracture characterization work to the subsurface.
- Determination of stress and depth effects on fracture aperture.

Construction and operation phase research would include:

- Effect of excavation techniques on fracture permeability near the repository.
- Additional heating tests for studying thermal loading and fracture aperture response.
- Testing of grouting and sealing methods for fractures.
- Conducting hydrological and radionuclide field experiments under induced isothermal and nonisothermal conditions.

Post-operational research would include:

- Testing of geochemical and piezometric instrumentation techniques for post-operational monitoring.
- Testing methods of borehole and shaft sealing.
- Monitoring the excavation while allowing it to flood.

In summary, the results of these experiments would be used to evaluate and improve the predictive capability of numerical and physical models; to evaluate and improve exploration, testing, and monitoring procedures; and to provide experience for construction and decommissioning of underground repositories.

5. FIELD TESTS FOR RADIONUCLIDE TRANSPORT

Field tests are needed as a basis to predict movement of radionuclides that may migrate from a waste respiratory. Radionuclide transport depends on several groups of factors including the geometry of fractures which govern flow, and the chemical and sorptive properties of the fracture surfaces.

Fracture geometry governs dispersion by defining the flow paths which water containing radionuclides must follow. Fracture geometry includes spacing, orientation, continuity and aperture, and it governs the magnitude and direction of mass flow rate and velocity. Spacing, orientation and continuity determine the degree of fracture interconnection and the number of possible flow paths in the system. Fracture aperture and hydraulic gradient govern the velocities and mass rates of flow in the fracture network.

Some reorientation of fluid particles will occur at the intersection of any two fluid-conducting fractures. Radionuclides entering such an intersection through one fracture will, in whole or in part, be reoriented to flow in the other fracture and will generally be diluted by fluid from the other fracture. With flow reorientation and dilution occurring at every intersection encountered, increasing dispersion will occur with distance from the source of contamination. Dispersion will

also occur within individual fractures due to surface irregularities, diffusion, and flow velocity differences resulting from boundary shear effects.

The chemical and sorptive properties of fractured rocks govern the loss rate of radionuclides to the rock matrix. Radionuclide loss may occur due to chemical reaction with the host rock and sorption by the host rock. The rate at which these phenomena occur in a given situation is governed by exposure time and surface area of the fracture system. These effects are larger and more difficult to assess in argillaceous rocks than in crystalline rocks because of their far greater surface area and their higher ion exchange capacity. In either rock, it is essential to determine ion exchange capacity in the field in order to assess the sorption factor. The broad objective of the field tests is to verify transport models based on laboratory determined distribution coefficient (K_d) values.

The data are best collected on a specific rock type and in a specific area, thus the details of geologic structure, stratigraphy, and hydrologic setting should already be known before planning such tests. The tests to be described will provide some of the hydraulic parameters but other tests should be conducted to provide some estimate of these parameters before planning a field K_d test. It would also be useful to determine the mineralogy of fracture coatings or fillings prior to planning the test.

As preliminary information, it would be useful first to determine the distribution coefficient and ion exchange capacity in the laboratory by batch tests and subsequently by column tests. However, these results

are only of value in designing the field test. They cannot be used as primary factors in estimating radionuclide retardation, especially in fractured rock systems.

Perhaps the best method of determining a field K_d value is to use a single well and either a packed-off fracture, fracture zone, or section of rock. At least two tracers will be required, one a non-exchangeable, conservative tracer such as tritium or fluorocarbons, and the other an exchangeable tracer such as strontium or cesium. Obviously, the chemical form of the tracer will be important and ultimately a simulated nuclear waste leachate may be used. Fluid containing the dual tracer would be injected into the packed-off section at a selected flow rate and for a selected period of time. The flow would then be reversed and fluid would be pumped from the well. The value of K_d is determined from the difference in return times for the exchangeable and non-exchangeable tracers.

A distinct advantage is obtained in performing this test in a single well rather than in moving the two tracers from one well to another, because the return flow path would be the same as the injection flow path, except for variations caused by dispersive flow paths. In a two-well test little is generally known about the flow path and if the exchangeable tracers never arrive at the sampling well, no data are collected and the test may be considered a failure.

In the single well test, the experiment could begin with short cycling times which could be progressively increased, giving information on the rates of ion exchange with increasing exposure to the fracture walls. An experiment could also be run in which the dual tracer is

pumped in, permitted to remain for some selected time, and then pumped out. This would provide information on ion exchange under equilibrium conditions.

If the flow paths are not dispersive and little exchangeable tracer is sorbed, the return of both tracers should occur as fairly sharp spikes, as shown in Figure 9. A slight time lag and a slight decrease in peak concentration would be expected for the exchangeable tracer due to sorption and chemical interaction. The return of both tracers as sharp spikes could indicate a small surface area of exposure, low sorption by the rock minerals, or inadequate exposure time.

Greater interaction between the tracer and the rock mass would result in a longer return time and a lower peak concentration for the exchangeable tracer, as shown in Figure 10. If the flow paths remain non-dispersive, the non-exchangeable tracer should continue to occur as a sharp spike.

If dispersion occurs because the fluid has passed through interlacing fractures, through fractures with uneven apertures, or through partially filled fractures, the return curves for both tracers will be flattened and peak concentrations reduced as shown in Figure 11. The arrival of the exchangeable tracer will lag as before, depending upon the degree of interaction with the host rock.

As a better understanding of physical and chemical conditions is obtained in the field, it may become feasible to perform two well tests and gain the advantage of a larger rock sample.

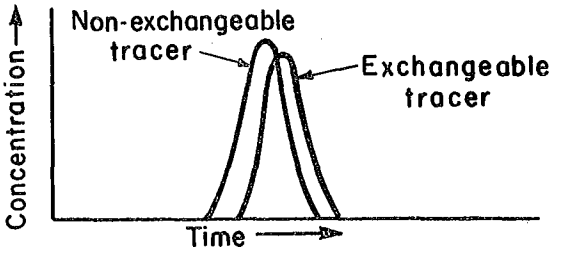

Fig. 9. Return concentration curves for non-dispersive medium with little loss of exchangeable tracer.

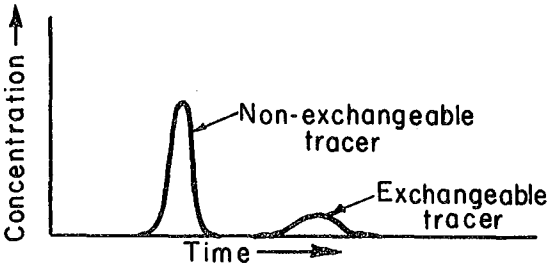

Fig. 10. Return concentration curves for non-dispersive medium with significant loss of exchangeable tracer.

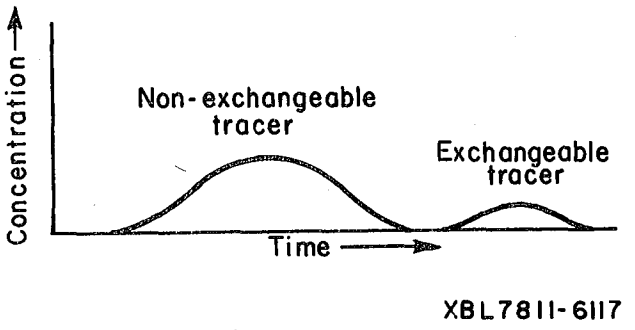

Fig. 11. Return concentration curves for dispersive medium with significant loss of exchangeable tracer.

The panel concluded that no additional equipment over that already discussed in previous sections would be required for field testing using radionuclides.

6. BOREHOLE, SHAFT AND TUNNEL SEALING

Boreholes, shafts and tunnels could serve as channels for contamination of the biosphere and will have to be effectively sealed once the decision is made that ready retrievability of stored waste is no longer required. Although no member of the panel was currently involved in research on this problem, a number of recommendations were made for research and development based upon a knowledge of the geotechnical problems involved. Development and characterization programs for sealing materials are presently being performed in Sweden (Pusch, 1977; Neretnieks, 1978) the Federal Republic of Germany, Oak Ridge National Laboratory, and Sandia Laboratories. These studies are being performed on laboratory and bench-scale samples up to a square meter in size, and most of the work has been done on salt and related rocks. Field testing of grouts for tunnel sealing has also been performed at Nevada Test Site.

No concensus was reached on whether the sealing of boreholes would be more or less difficult than a shaft or tunnel. Borehole sealing is simplified because the surrounding bedrock is generally less distrurbed than that near shafts and tunnels, yet the smaller size of boreholes makes control of backfill emplacement and selective grouting of major discontinuities considerably more difficult. It is recommended that excavation methods be selected which minimize disturbance of the host rock mass.

It was concluded that the art of borehole, shaft and tunnel sealing for long term confinement of nuclear waste is still in its infancy and that a comprehensive field testing program will be required before the effectiveness of such seals can be known. Criteria for determining effectiveness must be developed as well as criteria for identifying the required degree and duration of confinement. It should be recognized that the required life expectancy of a seal is finite and depends upon the half-lives of the radionuclides in the repository. A sufficient condition for sealing would be that the seal be as good as the host rock system; however, a necessary condition could be less stringent, and would depend upon long term safety requirements. Final seal design and emplacement will very probably be site-specific.

Research and development needs for borehole, shaft and tunnel sealing were identified, not necessarily in order to priority, as follows:

a. Perform a long term safety or consequence analysis of seal failure to determine the requirements to be met in final closure of a repository.

b. Consider clays and other natural minerals as sealing agents. Clays are plastic, offer sorptive capacity, and are the natural products of weathering processes for most crystalline rocks. They may, however, present emplacement problems, erode, undergo volume changes, and fail to support rock walls, thereby leading to disturbance to the host rock (Martin, 1975).

c. Consider the effectiveness of multiple layers of sealing materials to enhance physical similarity and chemical

compatibility with the host rocks. Sealing materials should retain their physical integrity over extended periods of time under the thermal, chemical and mechanical environment of the host rock, and should not significantly alter the chemical characteristics of native groundwaters.

d. Develop emplacement techniques such as pressure grouting to improve chances of sealing porous or disturbed zones. Bonding of sealing material to the host rock mass should be investigated.

e. Perform in situ tests, perhaps in an existing mine. Drill, seal and test a borehole for permeability. The program may continue over a period of years with a series of seals. The sealing material and host rock could be overcored and taken into the laboratory for microscopic analyses, and composition of waters that have permeated the seal could be analyzed to determine interactions that occurred.

f. Prepare documentation for quality assurance and quality control programs and technology transfer. Proper documentation will "leave tracks" if the program must be re-evaluated in later years. With documentation available, the processes, sealing materials, and techniques used to emplace the seal can be retraced if necessary.

g. Prepare a comprehensive report reviewing the state of the art for sealing a repository containing heat producing wastes.

7. RECOMMENDATIONS FOR DEVELOPMENT OF A RESEARCH PLAN

7.1 Introduction

In trying to build a research plan, the panel agreed that the research needs should be placed into a time framework. This can be risky but it was felt that it would be worthwhile to indicate how many years of research would be required to develop a reasonable assessment of the containment capabilities of a given rock mass for a 1000-year time period. It must be stressed that this suggestion of a four to five year period of research is tied to the provision of adequate funding and manpower resources and requires the preparation and implementation of a well-coordinated research plan. The panel did not attempt to assess the length of the research program that would be required in order to make predictions greater than 1000 years. It would be logical to assume that, having established a reasonable data base in the major research areas, the research program would focus on more specific research needs directed toward transients in the rock mass and assessing more carefully variations in the key parameters, hence defining the degree of uncertainty in the parameters measured and their significance in terms of the total system response.

Five research areas in fracture hydrology were identified and are shown in Figure 12. Keeping with the research plan approach, each area was assigned either a moderate or high priority ranking and either a moderate or absolute necessity ranking. The priority ranking refers to the timing of the research, i.e., whether research must be undertaken immediately (high priority) or whether it can be delayed for a short period of time (moderate priority). In most cases, this ranking reflects

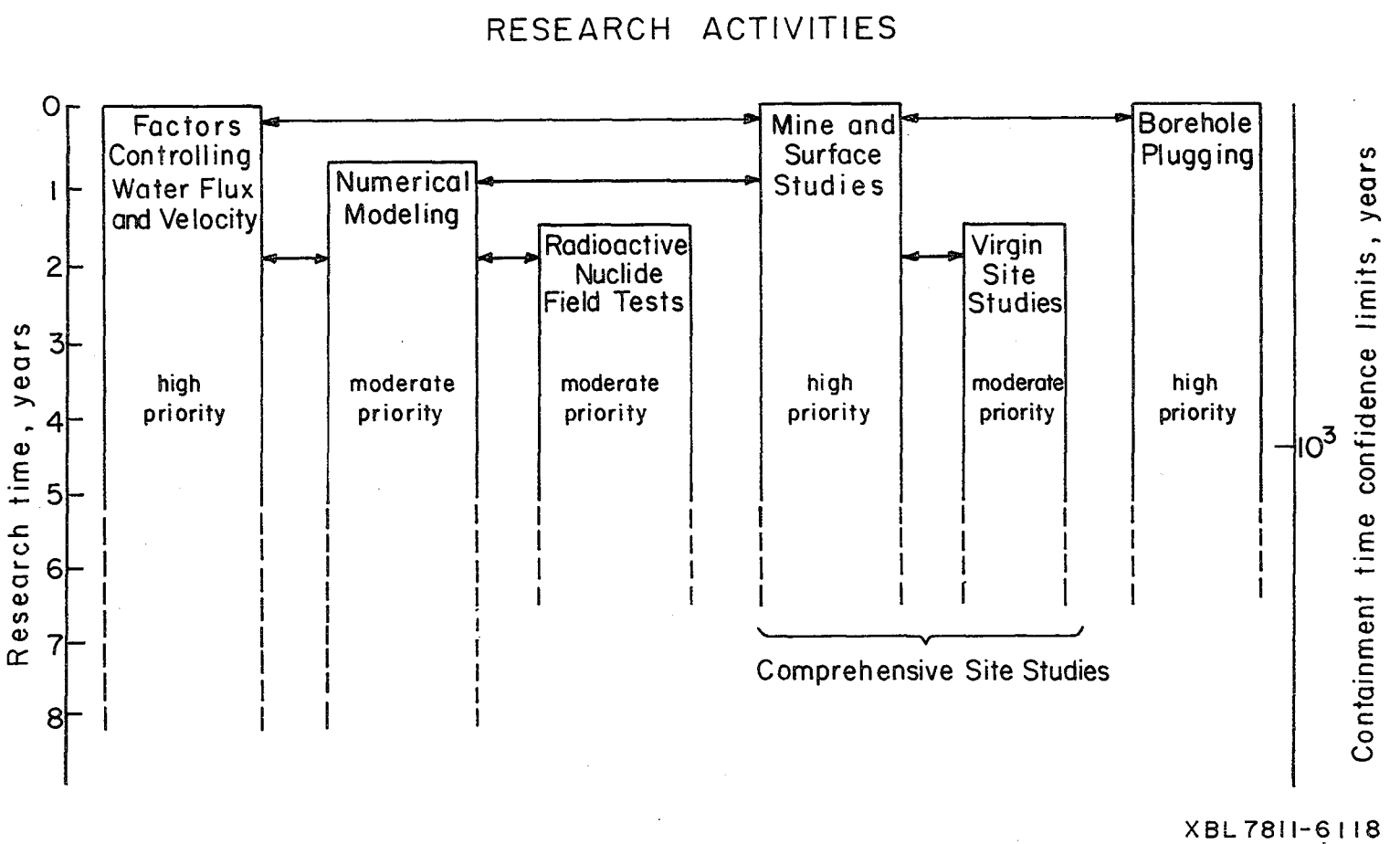

Fig. 12. Fracture hydrology research activities and priorities.

whether or not a given research area should be delayed until some other research area that it might be dependent on is more fully developed. The necessity ranking refers to the need to do the research; i.e., how essential it is to the overall project objectives. Thus a research activity can be an absolute necessity but have a moderate priority, indicating that it must be completed but that intensive work in this area can be delayed for a short period of time while priority is given to some other research activity.

Each of the five research areas are discussed in detail in the following sections with the appropriate research and instrumentation needs for each area. In this section, an attempt is made to summarize the key points in each of the five areas.

7.2 Water Flux and Velocity

Our understanding of the factors controlling water flux and velocity in fractured crystalline and argillaceous rocks is very limited. The existing data base in this area needs to be greatly expanded. This work must be given a high priority and is an absolute necessity in that many other components of the research program, including numerical modeling, cannot be brought to a successful conclusion until a significant part of this data base has been accumulated.

Water flux and velocity research needs can be grouped under the following parameters: permeability, pressure gradient, and porosity. For permeability, special emphasis was placed on finding methods of determining the directional permeability fractured rock. Five different approaches were suggested. These approaches are (1) the discrete data approach; (2) the Louis and Pernot (1972) approach, consisting

of multiple packer injection tests in boreholes oriented with respect to assumed principal permeability axis and measurement of the fluid pressure changes near the injection zones; (3) drilling of oriented boreholes and conducting injection tests with increasing packer spacing; (4) standard packer injection tests in conjunction with detailed geophysical measurements; (5) use of ratio pump tests for basalts and argillaceous rocks. It is important that these different approaches be assessed in field environments that have simple and complex fracture geometries. The five approaches should not only be applied to one specific site but to other locations in different lithologic and tectonic settings. The equipment needs associated with this work mainly involves tools for better defining fracture geometry, specifically:

- Improved borehole TV cameras
- More use of impression packers
- More extensive use of triple tube split inner barrel coring equipment.
- Review of existing borehole survey equipment for reliability and accuracy.
- It was also recommended that 76 mm be adopted as a standard borehole size.

For rock of very low permeability constant head injection tests will prove inadequate, hence equipment for transient (pulse) tests should be developed. Other major research needs relating to permeability are

- Tests to determine continuity of fracture systems: large scale tests around underground openings, cross hole pulse or tracer tests, or modeling studies.
- Psychrometric systems for measuring humidity in controlled ventilation tests in mines.
- Laboratory investigations of fracture permeability including tests for fracture permeability versus temperature and an investigation of the effect of sample size on test results.

Improvements in our ability to determine hydraulic potential in rock masses depend on improved equipment and emplacement procedures for piezometers. The needed improvements will allow identifying long-term pressure trends and monitoring waste repositories.

Research is needed on methods of determining the effective porosity of fractured rocks, especially with regard to determining what is an "equivalent porous medium" for modeling.

There is a need to develop tools for tracer tests including downhole tracer detection, downhole gas chromatography, and a downhole tritium probe.

7.3 Numerical Modeling

The state-of-the-art of numerical modeling is well-developed but considerable work remains to be done on models for fractured crystalline and argillaceous rocks. These models are needed so that water flow and radionuclide short-term near field, and long-term far field aspects of a repository can be simulated. The main research needs for numerical modeling in decreasing priority are (1) identification of the key input parameters and their description to provide

for the proper interface between discrete and continuum models; (2) model studies combined with field and laboratory tests to investigate coupling terms between stress, flow, and temperature equations; (3) incorporation of sorption in transport models; (4) development of coupled 3D stress-flow-temperature models; (5) inclusion of parameter uncertainty in models; (6) modeling dispersion in fractured media; (7) solution of the inverse problem for transport in fractured media; and (8) modeling of fracture formation and propagation.

In numerical modeling, a primary concern is model validation, and this will require involvement of the modelers in the design of field and laboratory experiments. Large-scale field tests with known initial and boundary conditions are absolutely essential.

7.4 Comprehensive Site Studies in Mines and Undisturbed Rock Masses

The need for additional in situ mine studies was strongly supported by the fracture hydrology group. It was recommended that at least three to four comprehensive programs like the Stripa program be undertaken in different geological, hydrological and tectonic settings. It was recognized that using existing mines has limitations such as perturbations induced by the mining and the geological setting of the mine, both of which are different than those for proposed repository sites. It was thus recommended that a test-site facility be constructed in an area of minimal disturbance (thermo-mechanical and piezometric) and in a potential site for a repository or in a site having a similar geological and hydrological environment to that of a potential repository. The development of this site would be preceded by comprehensive surface studies, installation of borehole monitoring systems, prediction of

subsurface conditions followed by excavation, and verification of system response as well as conducting a set of experiments similar to those in the Stripa program.

7.5 Radionuclide Field Tests

Radionuclide field tests are an absolute necessity if predictions of long term containment are to be reliable. The broad objectives of the field tests are to verify transport models based on laboratory distribution coefficient (K_d) data. Field data on K_d may be obtainable from single well or two well tests. Modeling will, however, be incomplete until factors controlling water movement are understood, hence this research is of moderate priority dependent on water flux and velocity factors.

7.6 Borehole and Shaft Sealing

The final research area identified was that of borehole, shaft, and tunnel sealing. This area is assigned a high priority, and there is an absolute necessity to pursue a vigorous research program. Boreholes are needed in order to adequately explore and assess a given rock mass. Our ability or lack of ability in borehole sealing may determine how many boreholes we can drill in a given area before we compromise containment integrity.

Research and development needs for borehole, shaft and tunnel sealing were identified, not necessarily in order of priority, as follows:

a. Perform a long term safety or consequence analysis of seal failure to determine the requirements to be met in final closure of a repository.

b. Conduct experiments with clays and other natural minerals as sealing agents.

c. Consider the effectiveness of multiple layers of sealing materials to enhance physical similarity and chemical compatibility with the host rocks.

d. Develop emplacement techniques such as pressure grouting to improve chances of sealing porous or disturbed zones.

e. Perform in situ tests, perhaps in an existing mine, for drilling, sealing, and borehole permeability testing.

f. Prepare documentation for quality assurance and quality control programs and technology transfer.

g. Prepare a comprehensive report reviewing the state of the art for sealing a repository containing heat producing wastes.

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GEOCHEMISTRY

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GEOCHEMISTRY

1. INTRODUCTION

1.1 Constraints

Discussion of geochemical aspects of radioactive waste disposal in crystalline and argillaceous rocks was limited by constraints stated by the organizers of the workshop regarding the general nature of possible repository sites and the waste form.

As to repository sites: A potential repository is assumed to be an excavation in crystalline or argillaceous rock at a depth of several hundred meters below the ground surface. The repository is thus below the regional water table and would be expected to fill with water within decades or a few centuries after emplacement of the waste. Possible sites above the water table or at great depths were only briefly discussed; consideration of such sites, however, should not be excluded *a priori* but were outside constraints imposed by the charge.

As to waste form: The waste is assumed to be in solid form and enclosed in a canister. In most discussions the waste form was assumed to be either spent fuel elements or high-level reprocessed waste incorporated into borosilicate glass. The canister was assumed to be metal, presumably stainless steel, copper, lead, titanium, or some combination of these. Other possible materials for both the solid waste and canister were briefly considered, and continuing research on such alternatives is recommended.

The crystalline rocks considered for disposal media were granite and basalt, with both terms used in a wide sense. Argillaceous rocks were assumed to include all sedimentary rocks with a high proportion of clay minerals, and thus to range from soft material consisting chiefly of kaolinite, montmorillonite, or illite to hard and brittle argillite. Also discussed was volcanic ash or tuff, both fresh and partly devitrified or zeolitized.

Times necessary for isolation of the waste from the biosphere were assumed to be of the order of a thousand years for the fission products and at least a million years for the long-lived actinides and their daughters. No formal limit was set on the maximum acceptable rate of escape of radionuclides from a repository into the biosphere, but it was implicit in the discussions that concentrations in an escaping fluid must be kept below maximum permissible concentrations (MPC) and it was recognized that, as in the past, MPC limits are likely to be lowered with time.

The repository site was assumed to be located in an area of tectonic stability with no record of volcanic activity or active faulting for many millions of years. The depth is assumed to be sufficient to preclude the possibility of damage from weathering or erosion, even under a drastic change of climate.

1.2 Barriers to Radionuclide Movement

When a repository is filled and sealed, solid waste in canisters will be embedded in crystalline or argillaceous rock. Each canister could be surrounded by packing material having the properties of low

permeability and high sorbency, and this same material could be present as backfilling of the repository cavity.

The temperature regime of the potential repository will depend on the concentration of waste in the canister, the age at emplacement, and the canister placement in the repository. No temperature estimates were provided by the conference organizers. In our deliberations, we assumed that the maximum temperature at any canister wall will not greatly exceed 100°C. If much higher temperatures are contemplated, it is imperative that hydrothermal reactions and thermodynamic constraints be considered in depth.

Although the surrounding rock will have been chosen for its low permeability, groundwater is expected to gradually invade the repository. The rate of movement is uncertain, but possibly within a few decades and certainly within a few centuries all material around the waste canisters will be saturated with water.

In contact with warm groundwater the canister metal will gradually corrode, and eventually water will penetrate to the waste. The waste form will presumably have been made as stable and nonleachable as possible, but eventually radionuclides will enter the regional groundwater system and be carried with it to its point of discharge, thus reaching the earth's surface.

The concentration of radionuclides in groundwater discharge can be minimized by four barriers to their movement. First is the canister: as long as a canister remains intact, no water enters and no radionuclides escape. The second barrier is the waste form itself. If the material dissolves only slowly, the rate of release of radionuclides

will be low. Even if the material dissolves or reacts rapidly, though, the rate of release of radionuclides to groundwater would also be low if the radionuclides immediately formed solids of low solubility. Third is the packing or backfill material, which can be designed to adsorb and hence retard movement of escaping nuclides. A final barrier is the host rock itself, in which water flow rates should be low, and which can retard radionuclide movement by sorption and ion exchange. Ideally any of the barriers should be capable by itself of blocking movement of radionuclides or keeping their rate of discharge within acceptable limits. All four acting together provide redundancy and add to the safety of a potential repository.

The geochemistry group considered the chemical aspects of each barrier. Several related geochemical topics had to be examined in conjunction with barriers, including methods for dating groundwater and for determining rates of groundwater movements, the general behavior of particular radionuclides in solution, and the behavior of gases released by fission of actinides, radioactive decay, or by radiolysis.

2. THE ROCK BARRIER

The geochemical tasks in evaluation and assessment of the suitability of a given rock mass -- crystalline or argillaceous -- must include detailed descriptions of the geochemical environments as they exist before disposal activities. Any changes in geochemical regimes accompanying and following mining and disposal operations will have to be measured against this background. Furthermore, these studies provide the basis for predictions with respect to the movement

of radionuclides from the disposal site. The regional aspect of such an investigation for each site has to be stressed.

The geochemistry of water migrating through rocks is controlled initially by conditions existing in infiltration areas and is changed with increasing residence time by reactions with rock minerals. Emphasis has thus to be placed on understanding the "geochemical evolution" of waters encountered at potential disposal sites since this may permit evaluation of processes and reaction rates typical for a given environment. This, in turn, can be used in constructing models used to predict geochemical responses to perturbations imposed by disposal of chemically foreign material into a rock mass.

Geochemical investigations of groundwater samples must include field determination of a number of parameters, amongest which pH and Eh are the most important (Wood, 1976; Hem, 1970). Field pH determinations are reproducible to better than 0.1 pH units; it would, however, be desirable for geochemical interpretations to measure to 0.02 units. Major difficulties, though, are inherent in Eh measurements and interpretations. Some analytical problems might be overcome through the use of gold electrodes rather than the conventional platinum electrode. This does not solve interpretative aspects and therefore it is recommended that conventional Eh measurements be supported by dissolved oxygen analyses and determinations of redox couples as they occur in the sulfur, manganese, arsenic, iron, and nitrogen systems (Thorstenson, 1970).

Laboratory analysis must include all major ions and possibly the trace elements which compete with radionuclides for exchange sites.

Mineralogic and chemical analyses should also be done on fracture minerals, because comparisons of water with fracture mineral chemistry may permit determination of specific partitioning coefficients.

Total organic carbon analyses in groundwaters from shield environments show that organics are present even at several hundreds of meters depth. Since organics may drastically affect the movement of radionuclides, they are discussed below in detail. Here it suffices to say that major efforts will have to be undertaken to understand the nature and amounts of organic components in groundwaters.

Isotope analyses, including both stable and radioactive isotopes, are already an integral part of most field investigations. The significance of stable isotope analysis was discussed at a 1977 meeting in Austin, Texas (Witherspoon, 1977). No major new developments have occurred since then, except that the usefulness of such analyses in granite environments is being validatd in studies being carried out by LBL and KBS in Sweden, specifically at Stripa. Additional comments on the age dating of groundwaters are presented below.

2.1 Regional Investigations

In order to predict water-rock chemical interactions, it is necessary to understand the natural interactions which occur in the system being considered as a potential repository. Reactions in groundwaters must be defined considering the flow of that water, and the greater the length of flow and time of reaction investigated, the more profound will be the understanding gained. Measurements of a single point are thus not sufficient. By understanding regional water-rock interactions one can make progress in predicting what additional reactions might

occur by introducing waste material and in interpreting radioisotope (^{14}C, ^{36}Cl, ^{238}U-^{234}U decay series) data in terms of water ages.

Integrated regional hydrodynamic and geochemical studies should address such questions as:

a. What minerals are dissolving, and how fast?

b. What minerals are precipitating, and how fast?

c. What natural buffers control pH? Eh?

d. What exchange and/or sorption reactions occur?

With such information, one might then assess whether perturbations caused by introduction of waste will:

a. Cause other minerals to dissolve, and how fast.

b. Cause other minerals to precipitate, and how fast.

c. Exceed the natural buffer capacity of the system.

d. Exceed the natural exchange and/or sorption capacity of the system.

No regional studies fully answer these questions in silicate rock systems. At least least one such study has been done, however, in a carbonate aquifer (Plummer, 1977; Pačes, 1973).

A major difficulty in working in silicate systems presently is the lack of an adequate analytical method for dissolved aluminum at the levels of 1 to 0.01 mg/l. Such concentractions are typical of those thought to be present at pH's of 6 to 9 in equilibrium with common rock forming silicate minerals. This information is necessary for thermodynamic considerations related to natural groundwater as well as water-rock (backfill) interaction.

2.2 Ground Water Age Dating

This subject was considered at length at a meeting in Tucson, Arizona in March 1978. The recommendations and conclusions contained in the report of that meeting (Davis, 1978) were:

"Discussion and Conclusions

> "The workshop participants considered that the development of ^{36}Cl method of dating and the continued development of ^{14}C dating presented the most promise for dating very old ground water. Despite the requirement for very large water samples, a ^{81}Kr method was considered desirable for validation of the ^{36}Cl dates because the half-life of ^{81}Kr is ideal and its geochemical history is not complicated. Three additional methods, amino acids, uranium disequilibrium, and helium accumulation, also were considered to have strong possibilities of being useful. The development of a stable isotope chronology was considered very favorably, but the regional nature of the method and the work needed to establish local standard trends suggest that a period of many years may be needed for development."

All workshop participants agreed that more than one method of dating should be developed and that none of the major dating methods considered should be eliminated from further consideration at this time.

A possible source of error in using groundwater ^{14}C in fractured media was not discussed in this meeting but must be considered. If the interconnection of fissures is poor, a normal dispersion description such as is used for porous media may not be applicable. As an example of the type of error which may occur, consider flow in two parallel fissures. One has a long retention time where all ^{14}C decomposes; the other has a short retention time where no appreciable decay occurs. If, in sampling, equal amounts from each fissure are gathered and mixed, the resulting age as determined by a ^{14}C measurement would reflect flow in neither fracture. Similar effects occur if the rock has microfissures with appreciable volume but with negligible flow.

Apparent dispersion effects then may be larger than normally encountered in flow in porous media. The effects of large scale dispersion on the ^{14}C content of ground water have been discussed by Winograd and Pearson (1976).

It is therefore suggested that supplementary methods be used for dating groundwater. Use of two nuclides with different half-lives would decrease interpretive errors. Detailed investigations in fracture hydrology may provide some assistance in assessing importance of "fracture dispersivity". These questions are also discussed by the Fracture Hydrology Panel. Downing et al. (1978) describe the use of ^{14}C and tritium data to separate fissure and interstitial flow in a fractured limestone.

Attempts recently were made to validate ^{14}C water age data through comparisons with ^{39}Ar analyses and ^{85}K measurements. The latter is cosmic ray produced at a rate corresponding to 0.112 $\pm$ 0.012 dpm $^{39}Ar/l$ of argon (Loosli and Oeschger, 1978). Its half life, 269 years, makes it suited for age determinations of up to approximately 1200 years. The comparisons were very surprising because they seem to indicate that the ^{14}C ages were much too old. All analyzed samples contained measurable ^{39}Ar, indicating ages below 1000 years even when ^{14}C ages exceeded 20,000 years. These discrepancies <u>must</u> be resolved. As an encouraging note, preliminary comparisons of ^{14}C ages with ages obtained from the uranium decay series at Stripa are very favorable and both indicate that old water discharges at that site.

Very few attempts have been made to age date waters from largely impermeable argillaceous rocks. One can anticipate, however, that rather serious interpretation difficulties may arise: Water movement occurs primarily as fracture flow and sparse knowledge indicates that the water geochemistry is controlled primarily by "exchange" with pore fluids rather than geochemical reactions on fracture surfaces or the geochemical conditions of the recharge environment. Detailed geochemical and isotope studies in different argillaceous rock types are recommended. Critical here is the small sample size, and it might be necessary to employ new analytical tools such as linear accelerators or cyclotrons.

It should be pointed out that while the ground water ages will be important in establishing hydraulic parameters which control the distribution of groundwater flow in the vicinity of a site, the fact that groundwater at a site is old is in itself not a sufficient constraint to make the site suitable. That is, an important criterion for establishing site suitability is not how long it takes water to reach the site but how long it will take water to flow from the site to the regional discharge area. Thus, age measurements to determine site suitability, rather than to assist in establishing hydraulic parameters, should best be made on water discharging from the regional flow system in which the site is located.

2.3 Thermodynamic Studies

The importance of regional geochemical and hydrologic studies cannot be overemphasized. However, the interpretation of many field data requires knowledge of the mechanisms which caused, for example,

a specific partitioning of an ionic species between aqueous and solid phases. Such mechanisms cannot be investigated in the field but require extensive laboratory investigations and thorough knowledge of thermodynamic data on participating solids and aqueous species.

The present state of knowledge on inorganic aqueous solubility and solution species distribution of some radionuclides is fairly well understood. However, little is known about several of the actinides, especially Am, Cm, Np, and possibly Pu. For example, with present knowledge it is not possible to predict with any confidence the equilibrium solubility of many actinides in water at given Eh, pH, and solute concentrations. It is therefore not possible to make reasonable predictions of the behavior of many nuclides in the regional groundwater flow system. Nor is it possible to predict the efficacy of formation of sparingly soluble actinide compounds that retard movement of long lived nuclides.

2.4 Role of Organics in Promoting Mobilization of Radioactive Waste

Various trace elements, including many transition metals, heavy metals (e.g., Pb, Cd), trivalent rare earths, and actinides are known to form solution complexes with certain organics. Complexing with organics, both natural and synthetic, may increase the mobility of certain radionuclides in the environment. A recent study (Means, 1978) of low- and intermediate-level liquid waste burial grounds at the Oak Ridge National Laboratory (ORNL) has shown that ^{60}Co is being mobilized as a result of complexation with EDTA. EDTA is used in decontamination operations because of its powerful metal binding properties; it is this same characteristic which leads to radionuclide mobilization.

Evidence from this study suggests that EDTA also contributes to the migration of Pu, Am, Cm, Th, and Ra. Approximately 5-10% of the migrating ^{60}Co and about 30% of the ^{235}U and ^{238}U present in this study area are believed to be associated with natural organic acids such as humic and fulvic acids, which are derived from the soil. Humic and fulvic acids have significant but lesser complexation capacity relative to EDTA for many transition metals and actinides.

Complexing agents such as EDTA or natural organics may also be promoting radionuclide mobilization at other radioactive waste disposal sites around the country. For example, unexpected Pu solubility or migration has been observed at Hanford, West Valley, Maxey Flats, and the Chalk River facilities in Canada. Complexing agents are either present or believed to be present in waste at Chalk River, West Valley, and Maxey Flats.

2.4.1 Laboratory Studies Needed

The above section shows the need for quantifying interactions between radionuclides and natural organics. Crystalline, and in particular, argillaceous rocks which are being considered as potential waste repositories may contain significant amounts of natural organic materials which may be leached at the moderately high pH, moderate temperatures, and low Eh expected in deep, well-evolved ground waters. These natural organics form strong complexes with radionuclides even in trace (< 1 ppm) concentrations and thus increase radionuclide movement. Unfortunately the smaller molecular weight species with the greatest oxygen-bearing functional group content, which are the most likely constituents to be leached, are also those species which will form

the strongest complexes with certain radionuclides. Thermodynamic data for humic/fulvic materials are difficult to obtain because of their great heterogeneity. We suggest that humic/fulvic - radionuclide associations be further investigated in the laboratory, and in particular, interactions with actinides. Actinide retention is potentially critical to the concept of radioactive waste disposal because of the high toxicity of actinides, yet actinide-organic interactions have received little attention. It is at least necessary to know the minimum organic concentrations required to significantly increase actinide mobility.

Similarly, interactions between radionuclides and synthetic organics need further investigation. The presence of multidentate amino polycarboxylic acids such as EDTA is not anticipated in high level waste. Traces of synthetic organics used in reprocessing such as hexone (MIBK), tributyl phosphate (TBP), and Butex may be present in reprocessed waste. Rather small concentrations of these compounds or their derivatives compounds may cause a significant waste mobilization problem, hence waste chemistry should be carefully evaluated prior to disposal.

2.4.2 Field Studies Needed

The above discussion demonstrates the need for careful investigation of the organic geochemistry of each potential disposal site. Certain geologic disposal media, particularly argillaceous rocks, may contain sufficient leachable acidic organic material to promote radionuclide migration. The chemical compositions and especially the radionuclide

complexing capacities of soluble organics present at each site should be investigated.

2.5 Role of Colloids in Promoting Mobilization of Radioactive Waste

Some of the actinide elements whose compounds are highly insoluble may be transported as colloids. The colloidal particles may originate by disintegration of the glassy waste form, by a change in pH or ionic strength of the solution, or by adsorption of ions on clay particles. Observations made in Sweden (LeBell, 1978) suggest that colloids are not important in granite, but this should be verified.

2.6 K_d-values and Sorption Phenomena

In existing transport models, sorption phenomena are described using distribution coefficients -- K_d's. These are not thermodynamically significant variables, but can be measured with ease and are in a form suitable for direct inclusion in existing mathematical models for transport of chemicals in porous media.

The empirical mass dependent distribution coefficient, K_d (dimension: m^3/kg), seems to be the most easily measured quantity, but it is not a true thermodynamic constant and gives no indication of reaction mechanism or reversibility. Further discussion of this problem appears in Section 2.6.1.

It is probable that when transport models for fractured media become available, they will need surface dependent distribution coefficients, K_a, as input data. So far, mostly K_d values are available. Either direct measurements of K_a must be performed or existing K_d values must be recalculated into K_a values. For direct measurements of K_a, the surface of exposed rock (dimension: m^2)

must be determined. For recalculation of K_d to K_a the specific area (dimension: m^2/kg) of the sample must be measured. For both cases, measured surfaces may be totally misleading since mechanisms of sorption processes are not known. Moreover, mechanisms are probably different for different nuclides and possibly dependent on the water composition due to the predominance of different species in solution. However, conversion factors (dimension: m^2/kg) between K_a measurements for whole rock samples and K_d measurements for crushed material from the same samples can be calculated under proper representative chemical conditions if fracture mineralogy and bulk rock mineralogy are the same. The chemically active surface or the physical surface of the rock sample does not need to be measured by itself.

For use in transport models, K_a could be defined to include roughness of the exposed macrosurface. This would allow application of a migration model that assumes planar parallel fractures. Fracture roughness is a parameter of concern to fracture hydraulics which would also be useful for K_a (or K_d) determinations.

2.6.1 Equilibrium Processes

A thermodynamically correct description of an exchange reaction is written

$$bAX_a + aB^{b+} = aBX_b + bA^{a+}$$

with equilbrium constant:

$$K_{eq} = \frac{(A^{a+})^b \ (BX_b)^a}{(B^{b+})^a \ (AX_a)^b}$$

where the terms on the right represent the ratios of the thermodynamic activities of the cations in the liquid and solid phases. Radionuclides are expected to be present only in trace quantities, and therefore changes in their activities in either the liquid or solid phase will not affect activities of other species present in much greater amounts. Furthermore, it is assumed that the thermodynamic activities of trace species in solution are equivalent to their concentrations. If B, above, is a trace radionuclide of interest, and A is present in much greater amount, what is measured is:

$$K_d = \frac{(BX_b)}{(B^{b+})} = K_{eq}^{1/a} \frac{(AX_a)^{b/a}}{(A^{a+})^{b/a}}$$

but as the term on the right and the activity coefficients of B^+ and BX are not measured or known, the thermodynamic equilibrium constant, K_{eq}, is unknown (Borg, et al., 1976).

While K_d's may be measured with relative ease, it has not yet been demonstrated that they may be used instead of K_{eq}'s to yield accurate geochemical predictions. Such a demonstration is not possible without a body of K_{eq} data against which results of calculations using K_d data can be compared.

We recommend that all laboratory water-rock interaction studies, not just those on exchange and sorption phenomena, be designed so their results will be useful in rigorous thermodynamic calculations.

2.6.2 Kinetic Factors

The kinetics of sorption and desorption should be measured both for crack surfaces and for crushed material of different particle size. An analysis of a sorption-desorption rate may give an indication of the sorption mechanism. For example, a rapid sorption/desorption process has been observed for Sr, indicating a surface-dependent reaction mechanism; while for Cs, there seems to be some diffusion into the rock (Allard, et al., 1978). For a trivalent element like Am the sorption mechanism appears to be entirely different, indicating a volume-dependent reaction or irreversible precipitation probably due to extensive hydrolysis of the trivalent elements at pH values close to 7 (Allard et al., 1978). A thorough investigation of the different mechanisms of the sorption process is of utmost importance in order to understand the sorption capacity of various minerals and rocks.

For the initial study of sorption mechanisms it is suitable to select some proper model substances representing monovalent elements (e.g., Cs), divalent elements (e.g., Sr), trivalent elements (e.g., Am or Eu) and tetravalent elements (e.g., Th or U(IV)). These sorption-desorption measurements should be performed on representative minerals as well as rocks, and the effect of variation of chemical parameters such as pH, Eh and concentration of potential complex forming agents in the water must be measured. In order to intrepret the experimental data it is also necessary that reliable thermodynamic data on complex formation, especially for hydrolysis and solubility of the complexes that may be formed in natural water systems, be available.

Explanation in detail of the sorption mechanism will allow prediction of the gross sorption behavior at a certain site if relevant physiochemical parameters are known. Still, site specific determinations of sorption should be performed.

2.6.3 A Case Study: Sorption of Technetium

One of the fission products which significantly contributes to the long term biological hazard is technetium (as ^{99}Tc, half-life 213,000 years). Technetium occurs predominantly as negatively charged TcO_4^- ions in oxidizing aqueous solutions. Thus the sorption on silica minerals of the bedrock or a backfill material like montmorillonite would be expected to be negligible; this has been confirmed from laboratory measurements of distribution coefficients for such materials. Recently, however, it has been calculated from thermodynamic data and also confirmed from laboratory tests that the TcO_4^- ion can easily be reduced to the tetravalent state, leading to strong sorption on silica minerals or possibly precipitation as TcO_2 (Allard, B., et al., Science, in press). This reduction can be accomplished by the presence of soluble divalent ion or minerals containing divalent ion (e.g., in the $Fe_2O_{3(S)}/Fe_3O_{4(S)}$ system) at pH 6.5-9, which is the expected condition in most bedrock - ground water systems at great depths for both granitic and argillaceous rocks. The retention of technetium in the Oklo Reactor may very well be consistent with such a reduction process. Thus, the prevailing assumptions concerning hazards from technetium seem to be overestimated. The reduction and sorption of technetium should, however, be confirmed in situ under non-oxidizing conditions.

2.6.4 Model Validation and Data Needs

The times of concern for waste isolation are from 10^2-10^3 years for fission products to 10^5-10^{6+} years for actinides and iodine. Laboratory tests and field tests with artificial tracers can have times of 10^{-2} to at most 10^0 years. For credibility in any site safety analysis, it will be necessary to demonstrate a high degree of confidence in extrapolations to 10^{6+} years.

There are two approaches to validating such time extrapolations. The first is by making predictions based only on rigorously established bodies of theory. For example, the geochemical fate of nuclides at a site might be evaluated as follows:

a. All elements in a repository and present or potentially present are listed, and possible pressure-temperature ranges are established

b. Thermodynamic data are available on all possible combinations of the elements present in the P-T range expected.

c. Rates of reaction among all possible phases are known

d. Calculation of the geochemical state of the site at any time in the future could then, in principle, proceed.

Data needs 2 and 3 are too great to make this approach feasible. However, as studies are carried out, they should as far as possible be designed to produce data which can be used in theoretically rigorously correct calculation schemes.

In the second approach to validating time extrapolations, concepts and models developed from experiment are tested whenever possible against data from long-lived natural systems. Such tests cannot

prove the absolute correctness of experimental data and models, but they illuminate concepts and add subjective confidence to approaches which successfully predict observed field relations.

Natural geochemical systems which may parallel waste isolation schemes do not exist because many elements present in nuclear waste do not exist in nature. However, natural systems do contain some of the elements of concern (U, Ra, and Rn, for example) and/or elements with behavior perhaps analogous to others of concern (Rh for Tc, for instance).

A natural geochemical field validation study might proceed as follows, though many other approaches could be taken:

a. A system is identified in which the ground-water flow is well characterized. Flow characterization is needed, for without it aspects of coupled flow and reaction cannot be treated. The system might be under evaluation as an isolation site, but need not be if the chemical process being investigated or modeled is one which is general.

b. The best available laboratory data and conceptual and mathematical models are used to predict the behavior of some element of interest in the system.

c. Measurements on the system are compared with predictions and the inevitable disagreements used to improve the mathematical and conceptual models and to choose the types of laboratory data needed.

2.6.5 Recommendations

1. Initiate new and support existing basic research efforts aimed at elucidating the processes controlling sorption. These should include, but not be limited to:

a. Developing methods to measure and then measuring thermodynamically acceptable constants.

b. Developing concepts and mathematical models which use thermodynamically acceptable exchange data and which can be used to assess effects of chemically and hydrodynamically controlled reaction and transport rates.

2. Concurrently with basic research on sorption mechanisms, continue laboratory measurement of K_d's, but:

a. Assure that laboratory studies are made on materials (e.g., natural surfaces) and fluids representative of the natural environment.

b. Verify in the field, by injection tracer studies and regional hydrochemical studies, that the K_d's measured in the laboratory reflect the retardations observed. The Underground Test Facility, outlined in section 5.1 of Rock Properties, would be employed for many of these field tests.

3. BACKFILL

Backfill is an engineered barrier to radionuclide movement. It consists of material put around canisters and in repository openings (a) to reduce permeability in the immediate neighborhood of the canister; (b) to sorb some radionuclides; and (c) to support the canister in

the hole. It may also be injected or electrostatically emplaced as grout into cracks in the host rock to further reduce permeability.

The principal research on backfill material has been done in Sweden, but the research is incomplete because of inadequate time. Montmorillonite, zeolites, and magnesia were studied. Montmorillonite is probably superior to the others because zeolites with time may recrystallize into a rigid framework that would be subject to cracking, and the hydration of tightly packed magnesia might produce unacceptably high pressures. (Neretnieks, 1978) A mixture of 90% quartz sand and 10% montmorillonite has been proposed as having sufficient strength to support canisters and sufficient flexibility to resist tectonic disturbance. (reference) The mixture is preferable to montmorillonite alone because the pure clay becomes gelatinous when wet and would not support canisters. Mixtures of montmorillonite and zeolite were also judged to be unsatisfactory because the zeolite may form a rigid crystalline framework if present in sufficient quantities.

A thickness of 20 centimeters of the quartz-montmorillonite mixture was calculated by the Swedes to be sufficient to adsorb cesium, strontium, and the short-lived actinide elements. The long-lived actinides were not strongly adsorbed, and to retard them effectively would require a prohibitively large thickness of the adsorbent.

The quartz-montmorillonite mixture is also suitable for filling cracks in the host rock. Conventional cements cannot be used for this purpose because they would eventually acquire an alkaline pH, thus accelerating attack on a glass (if that is chosen to be the waste form). The Swedish work also suggests that montmorillomite might be emplaced

at fracture openings by electrostatic means (Neretnieks, personal communication at this symposium, 1978).

The long-term stability of montmorillonite is of concern, particularly at temperatures to be expected in a repository. The less the temperature increase, the fewer the changes in absorptive and plasticity characteristics of montmorillonite. The temperature rise can be controlled by aging of the waste and by adjusting concentration of waste in the glass, assuming that waste form is used. In Sweden, the waste temperature is expected to remain under 100°, and experiments have indicated that montmorillonite is stable up to this temperature. On the other hand, geologic evidence suggests that montmorillonite can change to other clays, particularly mixed-layer montmorillonite-illite, at considerably lower temperatures. In the U.S., temperatures up to 200° and higher are often mentioned, and at these temperatures montmorillonite would certainly be altered. The long-term effect of slightly elevated temperatures on montmorillonite under repository conditions needs further study.

Research is needed on alternative materials for the backfill. Many possibilities have been suggested, but little pertinent study has been done. Zeolites may be a good possibility, despite the rather negative Swedish expectation (Jacobsson, 1977). Manganese oxides have been suggested because of their ability to adsorb uranium, plutonium, cerium and americium. Olivine has the advantage that it would gradually alter to serpentine and expand into cracks and open spaces. Other possibilites are talc, glauconite, and celadonite. Crushed rock of the same composition as the host rock would ensure equilibrium with the local groundwater after fresh surfaces had been "aged". Volcanic

ash might be suitable, but its alteration products after long contact with warm water need investigation. Organic resins and asphalt, which are often suggested for backfill, should be avoided both because radiolysis may produce gas in large amounts and because they might introduce compounds into solution that would complex some radionuclides and thus favor their transport in moving groundwaters.

The possibility of choosing a backfill material that would aid in retarding corrosion of the metal canister should be considered.

4. CANISTER MATERIAL

Since the panel did not include any experts on corrosion, we were not able to consider the design of this barrier. In addition to engineering considerations based on the waste material itself, the panel on geochemistry suggested the possibility of designing the canister materials with the site-specific properties of the groundwater in mind.

Dissolution of the canister material will liberate the first wave of environmentally foreign ions to the backfill and host rock. It is hoped that these ions would not decrease the sorptivity of the surrounding materials. The only other suggested geochemical consideration was the possibility of incorporating into the canister packing a rapidly-moving tracer so that breaching of the canister by groundwater would be detected in observation wells. He^3 and fluorocarbons were briefly considered, but stability of the latter over extended time is unknown.

5. WASTE FORM

Problems of the solidification of radioactive wastes and of waste forms are discussed at length by the National Research Council (1978). For geologic storage, two commonly considered waste forms are a variety of glasses and the spent unreprocessed fuel itself. These forms, among others, have often been proposed when considering reprocessed military waste. Direct emplacement of calcined waste has been proposed, and disposal of salt cake presents additional problems. We did not consider liquid waste here because of earlier stated restrictions.

All of these forms generally use the total waste: fission products plus actinides. A variety of proposed methods which involve more complex handling, some of which require chemicals separation, include synthetic inorganic materials such as ceramics, oxides, and silicate minerals ("super calcine"). At a higher level of complexity are waste forms of metallic matrices, cermets, and microspheres of waste coated with impermeable pyrolytic carbon.

5.1 General Recommendations

In general the geochemistry panel felt that attention should be concentrated on the two present leading waste forms - borosilicate glass and spent fuel - for the purpose of safety analyses and for guiding current research. At the same time, effort on promising waste forms should continue. In part, decisions on alternate waste forms are outside the narrow confines of geochemistry: generation of low level waste, hazard to workers, cost, and many other considerations are necessary to evaluate a proposed waste form.

The one class of waste forms the group recommends against are those involving organic materials; in fact the group recommends a concerted effort toward removing traces of organic solvents from any waste forms proposed.

5.2 Recommended Research

5.2.1 Borosilicate Glass

There is a considerable body of work on borosilicate glass. Within the realm of geochemistry, there appears to be a lack of leach data for conditions between about 75°C at atmospheric pressures and 300°C at several hundred bars. The Swedish workers report (Lakatos, 1977) that the leach rate increases about an order of magnitude from 25 to 70°C at atmospheric pressure. At 300°C, the glass devitrifies to soluble phases within weeks (McCarthy, et al., 1978). The Swedish results were judged satisfactory for disposal purposes because the KBS plan generates ~70°C glass surface temperatures below ground after 40 years intermediate storage. However, the system currently anticipated in the U.S. will lead to temperatures possibly exceeding 100°C. Thus there are currently few data within the expected temperature range. Perhaps glass composition could be tailored to decrease leach rates in the presence of site-specific groundwaters.

5.2.2. Spent Fuel

Few data currently exist for the "mineralogy and petrology" of spent fuel -- the compounds present, their grain size, radiation damage, permeability, etc. Research is in progress in Sweden on the leaching of spent fuel at lower temperatures. Although the leaching of spent

fuel may be considered more chemical engineering than geochemical, these data will be needed for any geochemical model.

5.2.3 Geochemical Compatibility and Thermodynamic Data Needs

Any waste form should be as chemically compatible as possible with the canister material, backfill material, groundwater, and enclosing rock. Thus a more easily leached but chemically more compatible waste form might be desirable from an overall geochemical perspective.

Without additional thermodynamic data, it is not possible to assess actinide behavior following release from the waste-form matrix. If the solubility of actinides at the chemical conditions of the ground water environment, along with actinide transport as colloids or organics, can be shown to be low, then the other chemical barriers become less important. Conversely, high radionuclide solubilities would underline the importance of the other barriers.

At present we do not have an adequate thermodynamic data base to perform the fundamentally important solubility calculations and evaluate the enclosing rock's effectiveness in retarding nuclide movement. Our knowledge of actinide solution speciation is even worse; and we need this data before we can effectively design the other barriers. The obvious usefulness of radionuclide solubility and speciation data suggests that research in this area should receive high priority, as already stated in Section 2.2. If elevated temperatures are to exist in the vicinity of the canister, data should be obtained over the temperature range expected.

6. ADDITIONAL GEOCHEMICAL CONSIDERATIONS

Several topics not easily falling under the previous categories were considered by the Geochemistry panel; these topics are included here.

6.1 Gases Evolved in the Spent Fuel Due to Radioactive Decay

Gas evolution calculations made by Swedish workers (Kjellbert, 1978; Westerluud, 1978) report that the volumes of the gas evolved are rather small, with helium evolved from the decay of heavy nuclides giving the largest volume. It has been calculated that it will take more than one million years in PWR fuel to build up a pressure of helium large enough to destroy the tube encasing the fuel. For BWR fuel the pressure will not build up appreciably during this time period.

One source of gas may be the tube material itself (zircaloy) which may react with water and release hydrogen.

6.2 Radiolysis

The problem of radiolysis of the groundwater by nuclide radiation was considered. Radiolysis could occur either in the immediate vicinity of the high level waste or during transport of radionuclides by the ground water. Radiolysis would lead to the formation of oxygen and hydrogen, which if present in sufficient amounts, could collect into a gas phase or alter the oxidation state of the ground water, or both.

Theoretical studies (Christenssen, 1978) indicates that radiolysis can be made insignificant by proper choice of canister material. Equilibrium calculations of ground water in direct contact with the waste also indicated that no significant problems would result from

the volume of gas released. Although the calculations did not take into account the disappearance of radiolysis products by diffusion or other transport mechanisms, it is believed that taking them into account would not alter conclusions. Radiolysis in the vicinity of the waste form may produce an oxidizing environment that could lead to mobilization of actinides in higher, more soluble oxidation states. Subsequent diffusion or convective transport away from the site could lead to gross supersaturation of these species in a more reducing environment with the eventual formation of colloids that may perist unfavorably for long periods of time. The concentration of radionuclides expected to be present in the ground water some distance from the repository is expected to be so low that no significant radiolysis will occur.

The presence of natural catalysts in the ground water and adjacent rock surfaces, e.g. ferrous ion, manganous ions, and surface active clays and mineral surfaces, was considered as a potential means of eliminating radiolysis products. Further study would be required, however, to find out their effectiveness.

In summary, it is considered that radiolysis is not a matter of serious concern, but periodic reviews of its significance should be made as the conceptual design of a storage repository progresses.

6.3 Membrane Phenomena in Geologic Materials and Depository Design

Laboratory studies demonstrate that geologic materials can act as osmotic membranes (Coplen and Hanshaw, 1973; Hanshaw and Coplen, 1973; Kharaka and Berry, 1973), and there are some indications that such phenomena occur in the field (Hanshaw and Bredehoft, 1968).

If such phenomena occur in rocks, an understanding of them is essential to site selection and safety assessment. Membrane phenomena studies are important to sites where argillaceous rocks occur in the regional system and to studies of the hydrology of beds overlying salt deposits.

Two interrelated membrane phenomena are involved: osmosis and hyperfiltration. Osmosis occurs where a membrane -- geologically these are clay and clay-rich sediments -- separates two solutions of differing activity, i.e. differing solutions or concentrations if isobaric. Due to the negative charges on clay particles, anions cannot pass through the clay pores. As cations collect on the negatively charged clay platelets, they impede further passage of positively charged ions. Thus water may pass through the clay membranes but the solute is prevented from doing so. There is net passage of the high activity (less saline) fluid to the low activity (more saline) side of the membrane. If the more saline solution is in less permeable rock the pressure will rise in order to raise the activity of the low activity side until it is in equilibrium with the high activity side. Thus in osmosis a difference of concentration is the cause and a pressure differential is the result.

The reverse of osmosis is called hyperfiltration or, commercially, reverse osmosis. This occurs where a sufficient pressure differential drives the more concentrated solution toward the less concentrated solution through the membrane. In this case ions are excluded from passing through the membrane, and the concentration increases on the high concentration side. Thus in hyperfiltration a pressure differential

is the cause and differing concentration and ionic make up is the result.

In siting studies for the repository an understanding of osmosis is important for the following reasons:

a. Hydrological interpretation of direction of water movement. Hydrologic investigations usually begin by drilling exploratory wells, constructing a piezometric surface map, and, assuming gravity is the principal driving force, deducing the direction of ground water movement.

   These assumptions are quite adequate in water supply studies where permeable aquifers contain fresh water, but these are probably not the conditions of host rocks considered for a repository. Thus without an understanding of membrane phenomena the direction of water movement might be completely misinterpreted.

b. Field evidence of hydrologic containment. Clays act as as geologic membranes only when they are sufficiently compacted that the ionic double layer around the clay platelets overlap. If the pores are sufficiently large that a traversing ion does not come under the influence of the electrical field surrounding the clay platelets, the fluid movement will be primarily in response to gravity gradients. Thus if an osomotic pressure exists it demonstrates that the fluid is contained and no fractures or highly permeable zones exist in the membrane.

c. In addition, the operation of osmosis through small pores provides a cause for fluid containment aside from the permeability of the solid matrix. Thus fluid movement may not occur even in cases where the permeability and gradient indicate that it would.

In repository siting studies, an understanding of hyperfiltration is important in understanding the geochemistry of the ground water in the area. Explanations of the geochemistry of constituents of the ground water are sometimes an indication of the age and history of the water. Without an understanding of hyperfiltration an essential concept in this explanation may be missing.

Because most ground water investigations are not involved with low permeability rock containing saline solution, little attention has been given to the study of geological membrane phenomena. Several studies were done in the 1960's but until the National Waste Storage Program no current research was being done in the United States. The Savannah River Laboratory has a program to investigate membrane phenomena in the ground, including both osmosis and hyperfiltration. Projected experiments will deal with thin membranes where the membrane, the container of the dilute solution, and the container of the concentrated solution are well defined. In the ground the membranes are hundreds of feet thick and are conceptually difficult to separate from the containers of the two solutions. Field studies of individual cases as well as computer modeling of membranes in series will attempt to enhance the understanding of thick membranes.

7. INSTRUMENTATION FOR GEOCHEMISTRY

7.1 Downhole Fluid Sampling

For geochemical analyses, samples of fluids from known depth intervals must be delivered at the surface with no exposure to the atmosphere, drilling fluids, or dust caused by drilling. Positive displacement pumps to deliver such samples and packer technology to delimit the interval sampled exist. However, techniques and instruments to assure the freedom from in-hole sample contamination must be developed.

7.1.1 Effects on Borehole Fluids

It is necessary to determine what drilling technique permits the most rapid collection of uncontaminated sample. Air drilling leads to minimum invasion of the rock by drilling fluid; however, even a small amount of air entrained in the formation is difficult to remove by pumping and very seriously affects the oxidation potential and gas content of the water. The latter is especially annoying if rare gas analyses are to be made.

Drilling with mud is distinctly unadvisable, for it is notoriously difficult to free even highly permeable formations of mud without extensive pumping, and mud profoundly effects the ground water chemistry.

Drilling with water is possible but would have to be done in such a way as to minimize (a) contact time between the fluid and the formation to be tested and (b) the differential between the borehole and formation fluid pressures. Reverse rotary drilling should be investigated.

Organic drilling fluids exist and should be investigated to see whether they would permit the collection of uncontaminated samples.

Development of drilling technology facilitating geochemical sampling must precede any site evaluation drilling and so has immediate, high priority.

7.1.2 Field Methods for Identifying Drilling Methods Contamination

If water or an organic drilling fluid is used, it must contain some tracer, the presence of which in a sample signals contamination. Tritium could be used, but concentrations high enough for field measurement would be unacceptable. Chloro-fluoro-methanes, generally known by their duPont trade name "Freon," are soluble in water and can be detected by field-operable gas chromatographs to low concentration levels. The presence of small amounts of drilling water in a sample could thus, in principle, be detected. It is thought that they do not sorb on rock surfaces and that they are chemically quite stable in groundwater environments, but this needs to be verified.

The sorption and long term stability characteristics of chloro-fluoro-methanes in underground environments should be studied. If they are acceptable, equipment for their injection into the drilling fluid should be developed, and field chromatograph design should be optimized. This should be done immediately and with high priority. See also section 7.4.

Organic dyes have been used for groundwater tracing but will be unacceptable in the reducing environments which will be encountered during site investigations.

7.1.3 Importance of Sampling System Materials

Two materials have been proposed for construction and/or lining of water sampling systems: stainless steel and teflon. Materials

in contact with the water system are important because of their potential effects on water chemistry. Stainless steel is undesirable because it may absorb or catalyze the decomposition of organics or be corroded and release trace metals. Teflon is better from the point of view of trace metal release, although it too may sorb organics from the water. Teflon may also release plasticizer which would interfere with the ground water organic identifications, or fluorinated compounds which might contaminate ground-water tracer experiments if freons were employed as tracers. Teflon is probably preferable to stainless steel, but more research is needed on this subject.

7.2 Borehole Measurements

Most geochemical work will be done on samples of formation fluid, but certain in situ measurements would be useful.

7.2.1 Improved Resistivity Logging Methods

Conventional well-bore resistivity measurements (electric logs) are useful for differentiating fluids of different salinities, but their sensitivity to small differences in waters of low salinities is not great. Improvement in this capability would assist in determining regional chemical patterns and reduce the number of individual samples required. It should be given moderate priority.

7.2.2 Down-Hole Geochemical Sensors

It would be useful, but not essential, to have the capability to measure certain geochemical parameters in the borehole both during the exploration and during the operational phase of site development. Of particular interest are oxidation potential and specific ion activity measurements. The oxidation potential electrode itself, either gold

or platinum, can become poisoned with time, while specific ion electrodes may require periodic recalibration and also can become poisoned. The greatest lack is of long-lived reference electrodes which will operate consistently at the relatively high pressures of deep boreholes.

Development of electrode technology should have moderate priority.

7.3 Laboratory Techniques

Certain analytical methodology developments are necessary to permit adequate geochemical evaluations of flow in poorly permeable terrains. Techniques to measure thermodynamically valid descriptors of sorption are also needed.

We strongly recommend that all analytical methods used in site studies be standardized to permit confident intercomparison of results from various laboratories. Methods for the collection and analysis of material dissolved in water as considered acceptable by various agencies of the U.S. Government are given in chapter 5 of the National Handbook of Recommended Methods for Water Data Aquisition (U.S. Geological Survey, Office of Water Data Coordination).

7.3.1 Measurement of Sorption Properties

No standard technique exists for K_d measurement, let alone for the more difficult measurements required to define the sorption Ka's described above. Development of such methods is of immediate need and high priority.

7.3.2 Dissolved Aluminum Analytical Techniques

In waters of moderate pH values (5 to 7), aluminum in equilibrium with common aluminosilicate minerals occurs at the 10^{-6} gm/l level. Existing colorimetric methods are sensitive to aluminum at these levels,

but interferences from other ions ubiquitous in natural waters limit practical measurement sensitivity to about 0.1 mg/l, about the sensitivity of atomic absorption methods. Plasma emission spectroscopy may have adequate sensitivity and specificity.

It will not be possible to understand the aqueous geochemistry of waters in silicate rocks without an adequate method for aluminum analysis, so aluminum analytical development is of immediate need and high priority.

7.3.3 Radioisotope Measurements for Dating

Analyses for ^{14}C and other radioisotopes by present methods require 10^2-10^3 liter samples, and such volumes may be unobtainable from rocks of very low permeability. It is possible that some of the difficulties from interferences may be avoided by using field extraction methods (Presser and Barnes, 1974). Accelerator techniques being developed should make these analyses possible on samples of 1 to 0.1ℓ sizes. A previous report on Dating of Old Ground Water (Davis, 1978) recommended the rapid development of these techniques and we endorse this recommendation.

7.3.4 Organic Complexing Agents

In section 2.4, we gave high priority to site specific research on radionuclide mobilizing effects of natural and synthetic organic complexing agents. In conjunction with this is the need to develop new analytical tools for assessing this very important subject. Most existing tools for measuring organo-metallic interactions, including gel filtration chromotography, ultrafiltration, dialysis, ion exchange chromatography, and anodic stripping voltammetry, are rather qualitative

or do not measure the desired quantities. One recommendation is that the fluorescence properties of organo-metallics be further investigated. Research on analysis of organics is currently being carried out at Battelle-Columbus Laboratory by developing laser fluorescence methods utilizing tunable dye lasers.

The application of this approach to natural organics is suggested.

7.3.5 Colloid Characterization

We have also given high priority to research on radionuclide (particularly actinide) polymerization kinetics and mechanisms of colloid formation. One problem is the lack of instrumentation for observing colloids directly in the beaker and measuring colloid size. Molecular beams such as those being developed at Princeton University for work on silica polymerization kinetics may be applied to the actinides. We therefore support the development of instrumental techniques such as molecular beams for evaluating polymer and colloidal size.

7.4 Waste Monitoring

It is desirable that we provide ourselves an early warning system for early loss of integrity of buried waste cannisters. Research and development of monitoring procedures are in general of low immediate priority but should be accomplished within several decades following the onset of deep geologic burial. It was suggested that future monitoring might include sampling for the He which is produced by alpha decay.

We also feel, however, that advance planning is advisable. For example, it might be advisable to seal in the waste canister along with the waste a tracer which would be released upon canister rupture. Since the most desirable tracer would not interact significantly with

the surrounding rocks, it would therefore serve as an early warning to loss of canister integrity. Two such tracers have been suggested: ^{3}He and freon. The possible inclusion of these tracers in waste canisters requires early attention. Monitoring procedures are of lower priority and thus can be developed over the long term.

8. SUMMARY OF RESEARCH RECOMMENDATIONS

Detailed recommendations for geochemical research appear throughout the text and are summarized here, followed by a reference to the section(s) describing why they are needed. The priorities and timing of the several efforts in the context of site evaluation, selection, operation and post-operation are noted as follows:

Priority:	E:	essential
	I:	important
Context:	R:	site evaluation and risk assessment
	S:	site selection
	O:	operation and post-operation
Timing:		start and duration, years from now.

	Discussed in Section	Priority	Context	Timing
Laboratory Investigations				
Measure base thermodynamic properties of actinide aqueous and solid species important in waste degradation and ground-water transport processes.	2.3 2.6.4	E	R,S,O	0-continuing
Develop techniques and measure thermodynamically correct parameters to describe sorption phenomena.	2.6	E	R,S,O	0-continuing
Measure long-term mineralogical stability of proposed backfill material and effects of changes on its capacity to retard radionuclide transport.	3	I	O	0-10
Develop new and improve existing techniques for radioisotope age dating.	2.1	I	R,S	0-5

	Discussed in Section	Priority	Context	Timing
Measure stability and thermodynamics of waste forms and pertinent waste-rock-water interactions.	1.1 1.2 5 5.2.3	E	S,O	0-continuing
Assess the potential for actinide transport as colloids.	2.5	E	R	0-10
<u>Field Investigations</u>				
Perform regional geochemical studies of potential sites, closely tied to regional hydrologic studies.	2 2.1	E	R,S	As needed
Identify and measure the complexing properties of organic materials in ground water and the waste itself.	2.4 2.4.1	E	R,S	0-10
Investigate the effects of mixing and dispersion on the interpretation of radioisotope groundwater ages.	2.1	E	R,S	0-continuing

	Discussed in Section	Priority	Context	Timing
Measure empirical distribution coefficients in natural systems and under simulated field conditions in the laboratory.	2.6 4	E	R,S,O	0-continuing
Determine the nature of reactions controlling the oxidation potential of ground waters.	2	E	R,S	0-continuing
<u>Instrumentation</u>				
Develop drilling technology to minimize contamination	7.1	E	R,S	0-5
Standardize analytical methods used in site studies	7.3	E	R	as needed
Develop better analytical techniques for dissolved aluminum	7.3.2	E	R,S	0-5
Develop age dating on small water samples	7.3.3	I	R,S	0-10

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APPENDIX B

APPENDIX B

BIBLIOGRAPHY OF KBS TECHNICAL REPORTS

Including Swedish-American Cooperative Program

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APPENDIX C

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APPENDIX C

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This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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