Implementation of Long-Term Environmental Radiation Standards: The Issue of Verification (1979)

Pages
76

Size
6 x 8

ISBN
0309028795

Panel on the Implementation Requirements of Environmental Radiation Standards; Environmental Radiation Standards; Committee on Radioactive Waste Management; Commission on Natural Resources; National Research Council

Implementation of Long-Term Environmental Radiation Standards:

The Issue of Verification

A Report Prepared by the
Panel on the Implementation Requirements of
Environmental Radiation Standards
COMMITTEE ON RADIOACTIVE WASTE MANAGEMENT
Commission on Natural Resources
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This study was supported by the U.S. Environmental Protection Agency under EPA Contract No. 68-01-3931.

International Standard Book Number 0-309-02879-5

Library of Congress Catalog Card Number 79-87667

Available from

Office of Publications
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

PANEL ON THE IMPLEMENTATION REQUIREMENTS OF ENVIRONMENTAL RADIATION STANDARDS

E. Linn Draper (Chairman)
University of Texas at Austin

Seymour Abrahamson
University of Wisconsin

Neville G.W. Cook
University of California at Berkeley

Charles Fairhurst
University of Minnesota

Todd R. LaPorte
University of California at Berkeley

Constantine J. Maletskos
Gloucester, Massachusetts

George A. Thompson
Stanford University

L. Jan Turk
University of Texas at Austin

John W. Winchester
Florida State University

Staff Officers:

Richard I. Milstein

Susan M. Stuen

COMMITTEE ON RADIOACTIVE WASTE MANAGEMENT

Earnest F. Gloyna (Chairman)
University of Texas at Austin

Michael S. Baram
Bracken, Selig & Baram (Boston)

Stanley N. Davis
University of Arizona

E. Linn Draper
University of Texas at Austin

Patricia W. Durbin
Lawrence Berkeley Laboratory
University of California at Berkeley

John T. Edsall
Harvard University

Merril Eisenbud
New York University Medical Center

James A. Fay
Massachusetts Institute of Technology

John C. Frye
Geological Society of America
Boulder, Colorado

Harold L. James
Port Townsend, Washington

Roger E. Kasperson
Clark University

Konrad B. Krauskopf
Stanford University

Todd R. LaPorte
University of California at Berkeley

Joseph Lundholm, Jr.
National Aeronautics and Space Administration

Colin A. Mawson
New Brunswick, Canada

Frank L. Parker
Vanderbilt University

Thomas H. Pigford
University of California at Berkeley

Rustum Roy
Pennsylvania State University

Edward Wenk, Jr.
University of Washington

Staff:

Winfred E. Berg
Special Projects Officer

John H. Pomeroy
Technical Secretary

John T. Holloway
Senior Staff Officer

COMMISSION ON NATURAL RESOURCES

CONTENTS

PREFACE

In response to a request from the U.S. Environmental Protection Agency (EPA), the National Research Council, through a Panel of the Committee on Radioactive Waste Management, studied the problems of verifying the satisfactory implementation of (i.e., compliance with) environmental radiation standards for deep geologic repositories for high-level radioactive wastes. This report contains the major conclusions and recommendations of the study.

Verification of long-term compliance with environmental radiation standards can be carried out only by future generations. With the assumption that the repository must be safe for future generations, even in the absence of verification, the Panel felt that its most useful contribution would be to identify a procedure that would provide assurance that the long-term performance of a radioactive waste repository will in fact comply with such standards.

At the onset of this study, it was agreed by both the Panel and EPA to assume that, after final closure of the repository, no human supervision or action would be required. This assumption was considered necessary in order to avoid the obvious conclusion that a continuing monitoring and surveillance program would constitute an adequate long-term verification procedure. This assumption forced the Panel to seek other techniques that could provide the necessary assurance of satisfactory long-term repository performance. Throughout the course of this study, however, the Panel was aware that, after repository closure, monitoring techniques could be employed to observe selected repository parameters, as required or desired.

The Panel had to conduct its study without the benefit of certain critical information: first, the EPA has yet to set its standards; second, the U.S. Nuclear Regulatory Commission (NRC) has not yet completed its criteria for judging the suitability of sites for waste repositories; and finally, the NRC, which has primary responsibility for assuring that the EPA standards are implemented,[1] has not established a formal licensing procedure for accomplishing this task. It was, therefore, not possible for the Panel to

SUMMARY

High-level radioactive wastes from nuclear reactors are accumulating in the United States and throughout the world. These wastes, at present stored in near-surface facilities, may constitute a hazard endangering people and the environment. To provide more protection against this hazard than does present practice, several concepts for permanent disposal of the wastes have been proposed. The concept that has been most commonly considered is burial in an appropriately designed repository located deep below surface in a carefully selected continental geologic formation. In accordance with its responsibility to protect the environment, EPA is formulating environmental radiation standards to establish limits on releases of radioactivity from such repositories. The NRC has the responsibility to use these environmental radiation standards in licensing radioactive waste repositories as proposed by the U.S. Department of Energy (DOE).

This report addresses the requirements for assuring that environmental radiation standards have been satisfactorily implemented. The Panel approached this study with a number of initial assumptions: (a) only the terminal disposal of wastes in a geologic repository is at issue, not the temporary storage of wastes; (b) the environmental radiation standards will be applicable in the biosphere, including any aquifer of potable water ordinarily accessible to a significant number of people; (c) EPA will seek to ascertain whether or not its environmental radiation standards will be met by a specific repository, and will establish this assurance independently of the actions by other federal agencies; (d) the procedure to establish this assurance should be applicable regardless of the waste form or the geologic environment chosen; and (e) no human supervision or action will be required after final closure of the repository.

Verification, in the usual sense of the word, involving monitoring releases of hazardous material and comparing the measured release rate with established environmental standards, can only deal with present and past operations, even though present and past performance may be indicative of probable future performance. Verification that long-term future performance will continue to satisfy the

environmental radiation standards, therefore, cannot be established by monitoring present emissions; such verification can only be carried out by future generations. In its deliberations, however, the Panel concluded that a satisfactory degree of assurance of the probability that a repository's long-term performance will comply with such standards can be achieved. Because of the long time scale during which the radioactive wastes present a potential hazard to the biosphere, the isolation and containment of the radioactive wastes depend heavily on the geologic and hydrologic environment as perturbed by the construction of the repository and the wastes in it. The assurance procedure recommended by the Panel must include confirmation of the proposed site's suitability, and confirmation of the adequacy of the proposed repository's engineering design. The nature of subsurface media requires that special laboratory and field studies be made to evaluate the pristine characteristics of the proposed site, and that the effects of the repository on the site be studied by large-scale, in situ field tests. One of the tools to be used in this assurance procedure is predictive modeling of the possible long-term migration of radionuclides from the repository and the possible transport of radionuclides to the biosphere. Such predictive modeling will provide estimates of release rates and concentrations of radionuclides in the biosphere at various times and locations.

In the Panel's judgment, this procedure can be the basis for providing a satisfactory level of confidence that the underground repository will provide adequate isolation and containment of radioactive wastes during the period in which they present a hazard. The following conclusions and recommendations are made to provide assurance that environmental radiation standards will be satisfied.

CONCLUSIONS AND RECOMMENDATIONS

During the course of this study, the Panel concluded that the emplacement of radioactive wastes in properly designed repositories located deep below the surface in appropriately selected geologic formations can reduce the release rate of radionuclides to a level within the environmental radiation standards. While the radiation standards had not yet been established at the time of this writing, the Panel is of the view that the probable range of standards under consideration by EPA can be accommodated, if necessary by changes in the site selection criteria and changes to repository design and testing procedures. In order to provide this assurance, the Panel recommends:

- <u>that a procedure be adopted to ascertain whether a geologic site and the construction of a repository will</u>

provide adequate isolation of radioactive wastes to satisfy environmental radiation standards. This procedure should include a data acquisition program based on extensive experimentation, both in the laboratory and in the field, site exploration, and large-scale, in situ testing. These data, together with appropriate models based on a thorough understanding of the phenomena involved, should provide the basis for a quantitative prediction of releases of radioactive materials from the repository;

- that this procedure be a continuing process that includes evaluations of site suitability and satisfactory repository performance before construction, reevaluations during construction and prior to emplacement of wastes, and a final assessment before emplaced wastes are committed to disposal. Corrective actions, including removal of emplaced wastes and site abandonment, should be available options until final qualification and closure of the repository; and

- that the repository design and construction procedures limit to an acceptable level any adverse effect of excavations and of the emplaced wastes on the integrity of the geologic formation, i.e., the capability of the geologic formation to contain the wastes within it.

CHAPTER 1

INTRODUCTION

In order to protect humanity from the potential hazards presented by existing and steadily accumulating radioactive wastes from nuclear reactors, measures must be taken to isolate the wastes from the biosphere. One proposed means of isolation is to bury the high-level radioactive wastes[1] deep underground in geologic formations appropriately selected for their stability and retention characteristics. A principal attraction of deep geologic burial is that it may provide a practicable way of isolating wastes physically from the biosphere for very long periods of time. A principal concern about deep geologic burial involves the degree to which toxic components of these wastes may leak back through the subsurface media into the biosphere.

In accordance with its responsibility to protect the environment, EPA is planning to set long-term environmental radiation standards for radioactive wastes buried in this way. Once these standards are set, there is the concern as to whether or not a methodology can be established that can provide assurance that the repository's performance will comply with such standards. In view of this serious concern, EPA has asked the Panel to consider the feasibility of verifying future compliance and, if it decides it can be done, to describe how. Before addressing this question in detail, it will be useful to review some background information.

Most of the radioactive wastes now in existence were generated by either the commercial nuclear power industry, or the military programs that included the production of plutonium for use in nuclear weapons. In the latter case, the spent nuclear fuel, after irradiation, is removed from the reactor, dissolved in acid, and reprocessed to separate the plutonium and uranium from the remaining highly-radioactive fission products, actinides, and other nuclides. As a result of reprocessing for military operations, approximately 265,000 m^3 (U.S. DOE 1978) of radioactive wastes are now being stored in near-surface facilities at three major sites in the United States: the Hanford Reservation in the state of Washington, the Savannah River Plant in South Carolina, and the Idaho National Engineering

Laboratory in Idaho. Most of these wastes have been neutralized with sodium hydroxide and are in the form of insoluble sludges, soluble salt cake, and residual liquids.

Radioactive wastes are also generated by the commercial nuclear power industry. Although a small amount of commercial spent fuel has been reprocessed at the Nuclear Fuel Services facility in West Valley, New York, the vast majority of commercial wastes is still contained in the spent fuel assemblies themselves, which are being stored in large water-filled pools at the reactor sites. Because of concern about proliferation of nuclear weapons, current United States policy is to defer indefinitely the reprocessing of commercial spent fuel and the recycling of recoverable uranium and plutonium.

A potential risk to public health is presented by the current practice of storing radioactive wastes and spent fuel in surface and near-surface facilities. Therefore, final deposition of the military wastes is now planned in appropriately designed repositories located in carefully selected geologic formations in order to reduce the chance of any future release of radioactivity to the biosphere and its consequent risk to human health. Experimental storage of spent fuel in similar facilities is also under consideration. Regardless of whether additional wastes are generated, the disposal of the existing radioactive wastes in a secure long-term repository is essential.

NOTE

1 High-level radioactive wastes are defined by the NRC as "the aqueous waste, or its solidified product, resulting from the operation of the first-cycle extraction system, equivalent concentrated waste from subsequent extraction cycles, or equivalent waste from a process not using solvent extraction, in a facility for processing irradiated reactor fuels." Other significant wastes considered for burial in deep geologic formations include unprocessed, used fuel elements removed from a nuclear reactor, volatile radionuclides collected from fuel reprocessing plant off-gas streams, and wastes containing elements of atomic number greater than 92, in concentrations greater than 10 nanocuries per gram. (The limit of 10 nanocuries per gram has not been adopted in a formal NRC regulation. The federal agencies are, however, working with this number.) Hereinafter, all of the above will be referred to as "radioactive wastes."

CHAPTER 2

RISKS FROM RADIOACTIVE WASTES

Human beings and other living organisms have been exposed to vast numbers of agents, both physical and chemical, that can impair health. Ionizing radiation is such an agent: it may lead to morbidity and mortality (e.g., from induced cancers or adverse genetic effects) in some of the exposed population. To protect against the exposure of people to harmful amounts of radioactivity, federal standards have been instituted.

Radioactive wastes constitute an additional source of radiation that may adversely affect the population. If these wastes are disposed of in a well-designed repository, however, the incremental contribution to the population dose will probably be a very small proportion of the allowable dose limits, and the increase in the number of potential health effects would be minimal. On the other hand, if the wastes are not disposed of properly, the increase in dose might constitute an unacceptable risk to a significant segment of the population.

The ultimate concern about radioactive materials buried in a waste repository is their possible transport and release via various geological, geophysical, geochemical, and biochemical processes to the biosphere at levels that would have unacceptable biological consequences, particularly to people. The objective of a properly chosen site and properly designed, constructed, and sealed repository is to delay the release and transport of radionuclides into the biosphere to essentially negligible or acceptably low rates and quantities.

The most probable vehicle for the transport of radioactive materials from a repository to the biosphere is groundwater. The nature of the transport process can result in a gradual migration of these radionuclides, dissolved or entrained in groundwater, over a long temporal span. Because of geochemical retardation and radioactive decay, each radionuclide will have its own concentration profile along a transport path from the repository that will vary with time and that may not be in phase with any other concentration profiles. Thus, at any point beyond the repository and at any time, the relative importance of each radionuclide will vary. An appropriate evaluation of the containment of these radioactive materials will therefore require detailed and accurate calculations of the transport for each radionuclide, taking account of all processes that affect their movement, including their individual chemical properties, the chemical retention of nuclides by engineered barriers and by the surrounding geologic media, radioactive decay, and parent-daughter relationships.

The impact of radionuclides on the biosphere, especially on people, is measured in terms of radiation dose and its associated biological risks. Estimation of the radiation dose to various individuals and to population groups requires a description of radionuclide transport through the geosphere and the biosphere, as well as identification of all the critical pathways to people. At present, there is considerable experience in calculating individual and population radiation doses resulting from transport through the biosphere (see, for example, Killough and McKay 1976). On the basis of this experience, critical pathways in the biosphere can be identified and calculations of the radiation dose can be made with confidence in particular impact studies.

Because of the uncertainties of the future, it is desirable to rely on the stability of the natural barriers provided by the geosphere, as supported by engineered barriers, to provide the primary protection against any hazards of radioactive wastes. The effectiveness of these barriers is likely to change much more slowly over time than the dynamics of the biosphere. Furthermore, once the wastes are emplaced, these barriers are not easily accessible or amenable to disturbance by human activity. In determining future barrier performance, knowledge of the processes occurring among the waste form, canisters, engineered barriers, and geologic media is, therefore, of critical importance. These factors must all be investigated and their contribution to the waste isolation and containment systems assessed with appropriate thoroughness.

CHAPTER 3

ASSURANCE OF LONG-TERM COMPLIANCE

3.1 FEASIBILITY

The Panel has concluded that a satisfactory degree of assurance of the probability that a repository's long-term performance will comply with environmental radiation standards can be achieved. Such assurance will have to be based on an adequate scientific understanding of the geochemical and geophysical phenomena involved, an extensive data collection and test program, and the development of appropriate models and modeling techniques to predict the long-term performance of a radioactive waste repository. The level of assurance that can be developed will depend upon the adequacy of the scientific understanding of the phenomena involved, the quality and extendability of the data from which predictions are made, and the fidelity of the computer models and the real world. Performance predictions inevitably have associated with them degrees of uncertainty; this uncertainty can be suitably quantified by careful analyses of the component models and their individual contribution to the final prediction, comparison of real-world experience with similar transport mechanisms involving similar materials, comparative analyses between equivalent models, and carefully structured sensitivity analyses.

The confirmation of the future performance of a radioactive waste repository and, hence, the assurance of future compliance with environmental radiation standards, will require the proper selection and an accurate description of the repository's geologic environment, the waste form and its containment, and a comprehensive experimental program which includes laboratory and field studies. The Panel considers the methodology described in Section 3.2 as suitable for providing adequate assurance of long-term compliance of a repository with environmental radiation standards.

3.2 METHODOLOGY

Surveillance procedures for assuring compliance with environmental radiation standards, involving monitoring of emissions followed by corrective actions if necessary, can be used prior to the final closure of a repository, but cannot be applied to assuring future compliance with such standards over an extended span of time. A methodology for assuring long-term compliance with such standards must establish whether a geologic site and the construction of a repository within it will provide adequate isolation of radioactive wastes. The confirmation of site suitability and the assurance of future adequate repository performance must be a continuing process that includes evaluations before construction, reevaluations during construction and before emplacement of wastes, and a final assessment before emplaced wastes are committed to disposal. Corrective actions, including removal of emplaced wastes and site abandonment, should be available options until final qualification and closure of the repository. The following considerations, with a careful scientific analysis of each, should be taken into account.

3.2.1 Selection of Sites and Waste Forms

Sites for the waste repository must be selected to satisfy the NRC's geologic criteria for suitability. There should be a confident understanding of the past behavior of the geologic environment, including consideration of the probability and consequences of glacial intrusions, climatic changes, earthquakes, volcanoes, and other transient events.

The characteristics and properties of appropriately selected geologic sites that are currently stable and have been stable for long periods of geologic time can be expected not to change significantly during the expected time span for which isolation of radioactive wastes is required. Furthermore, the effectiveness of geologic media as barriers to the transport and release of radioactive materials from repositories constructed deep below the surface at such sites can be expected to continue. However, the disturbance of the inherent integrity of suitable sites caused by the excavation for construction and operation of a repository, and future interactions of emplaced wastes with the geologic media, introduce additional variables and uncertainties into the prediction of both the short- and long-term behavior of the repository. These factors must be taken into account in the prediction of the long-term performance of the repository.

The geologic criteria for radioactive waste repositories are being established by the NRC. Recommendations on general geological site selection have been made by other groups (see, for example, National Research Council 1978), and were not considered by this Panel.

Waste forms and containment should be chosen so that they are compatible with the host geologic formation, and can be kept in a retrievable mode for an appropriate period of time (see, for example, National Research Council [in press]). The wastes should be retrievable up to the point of final repository sealing, in case the repository is found to be inadequate at any time during the period required to establish the necessary performance assurance.

3.2.2 Investigation of the Site

A thorough scientific and engineering investigation should be made of the suitability of the potential site, <u>employing techniques that do not significantly impair the site</u>. Using a radionuclide transport model based on an adequate understanding of the chemical and physical interactions between the waste form, its containment (including the canister and engineered barriers), and the geologic media, a prediction must be made of the rates of release of radionuclides to the atmosphere and into aquifers of potable water ordinarily accessible to a significant number of people. If the predicted value of these release rates and concentrations, taking into account its uncertainty, is sufficiently below the prescribed standard, exploratory excavations may begin.

3.2.3 Exploratory Excavation to Demonstrate Adequacy

A comprehensive experimental program using exploratory excavations at the proposed depth of the repository should be conducted to supplement the earlier site investigation. The program must include construction and testing of representative lengths of shafts and tunnels for purposes of demonstrating whether or not the materials and techniques ultimately to be used in sealing the repository are adequate. For example, seals can be tested by pumping water or gas behind them and measuring the response of the seals and the surrounding rock to resulting fluid pressures and rock stresses. Tests, such as thermal experiments using electrical heaters to simulate waste canisters, should be commenced as early as practicable during the construction phase of the repository, so that they may be continued for a significant period of time. The data obtained during the exploratory excavation should be used to provide an updated and more confident prediction of release of radioactive materials from the repository. If the predicted release, taking into account its uncertainty, still meets the prescribed standards, excavation of the repository site may continue. If the predicted release, taking into account its uncertainty, does not meet the prescribed standards, the site should be abandoned unless the waste form can be modified or other engineered barriers utilized to compensate for whatever geological inadequacies are found.

3.2.4 Measurements During Excavation

At all stages during excavation of the site, measurements should be taken and the results compared with earlier analyses and predictions. This measurement program should include mapping of geologic features; large-scale testing of the effects of the excavation on the physical, mechanical, and hydrological characteristics of the rock mass in the vicinity of the proposed repository; and detailed investigation of the geochemical characteristics of the geologic environment pertaining to radionuclide transport within it. The new data thus obtained should be used to provide an updated and more confident prediction of the release of radioactive materials from the repository. If the predicted release, taking into account its uncertainty, still meets the prescribed standards, clearance may be given to emplace the wastes in repository sections for which adequate data are available, while preserving the option to retrieve the emplaced wastes, if necessary, and to abandon the site.

3.2.5 Measurements During Emplacement

For an appropriate period during which the wastes are being emplaced and are still retrievable, measurements of critical parameters should continue in order to provide additional information on the initial performance of the repository. The measurement program may include, for example, observations in the rock and back fill of changes in displacements, stresses, temperatures, and groundwater flow that may be induced as a result of emplacement of the wastes, and their radioactive and thermal effects. The new data thus obtained should be used to provide an updated and more confident prediction of the release of radioactive materials from the repository. If the predicted release, taking into account its uncertainty, continues to meet the prescribed standards, the repository may be sealed.

The objective of these analyses and laboratory and field experiments is to provide a scientific understanding of the chemical and physical processes involved in the underground isolation of radioactive wastes that will enable the development of comprehensive computer models that can predict with adequate confidence the future performance of such a repository. The objective of large-scale, in situ tests prior to site selection and during the construction and early operation of a repository is to provide supporting field data and experimental confirmation of the earlier expectations and predictions. If this confirmation is provided, then the Panel considers that reasonable assurance that environmental radiation standards will be satisified for the required time can be adduced.

CHAPTER 4

INFORMATION REQUIRED TO ASSURE LONG-TERM COMPLIANCE

Assurance of future compliance with environmental radiation standards requires (a) the confirmation of the proposed repository site's suitability, which is concerned principally with measurements of the pristine geologic conditions of the site, and (b) the confirmation of an adequate engineering design, which considers the effects of the excavation, construction, and operation of the repository on the geohydrologic environment, the interaction between the wastes and the geochemical environment, and the performance of engineered barriers to the release of radioactive materials. In confirming the adequacy of an engineering design, testing of representative lengths of the shafts, tunnels, and other major components affecting the long-term integrity of the repository (referred to as large-scale testing) must be completed to provide actual test data with minimum scaling errors. The use of these data should reduce the uncertainties in the predictions, thereby providing the required degree of assurance that the environmental radiation standards will be satisfied.

Predicting a repository's long-term performance to comply with environmental radiation standards involves issues without precedent. While some of the factors involved in making such a prediction are well understood, others are not. Accordingly, the Panel adopted the stance that, in order for such a prediction to provide adequate assurance of future compliance, the evaluation of every conceivable circumstance that may adversely affect the repository's performance would be required. Based on this requirement, a diversity of considerations are raised in the ensuing discussion. To avoid prejudging the outcome of a proper analysis, no overt attempt has been made to draw distinctions concerning their relative importance. The intention of the Panel has been to ensure that the procedure used to confirm the suitability of a repository site and its engineering design to comply with environmental radiation standards will be careful and thorough. The procedure itself should reveal the relative importance of the different factors and issues.

This chapter describes the information necessary to assure long-term compliance with environmental radiation standards.

4.1 CONFIRMATION OF SITE SUITABILITY

The information required for confirming site suitability may be divided into three main categories: geophysical, geohydrological, and geochemical.

4.1.1 Geophysical Information

Confirmation of whether or not a geologic site is suitable for a radioactive waste repository will require quantitative evaluation of all factors that bear on the mechanical stability and integrity of the rock mass within the region affecting the repository throughout its lifetime. This evaluation must be updated periodically as significant new information becomes available and must include, as a minimum, consideration of the following: (a) seismic and tectonic activity, (b) volcanic activity, (c) existence of major faults, (d) ambient stress conditions and rock mass stability, and (e) geothermal gradients, thermal conductivity, and heat capacity.

4.1.1.1 Seismic and Tectonic Activity

Within the site area, either slow and continuous deformation or sudden fault offsets could be important, because they may open cracks, change geohydrologic properties, or disrupt part of the repository itself. Earthquakes outside the site area, but severe enough to cause intense shaking at the site, are of concern for similar reasons. The historical record of earthquakes in a large region surrounding the site should be documented (as is required by the NRC for nuclear power plants). Data need to be presented both as maps and as statistical summaries (e.g., the frequency of earthquakes plotted against maximum intensity). Because the historical record is short relative to the frequency of large earthquakes, the geologic record and the in situ stress determinations must be used to establish the long-term probability of earthquakes. The value of in situ stress determination is discussed in Section 4.1.1.4.

4.1.1.2 Volcanic Activity

The geologic record of the history and frequency of past volcanic activity should be established over a region around the site or in the geologic province of the site large enough for the probability of future activity to be determined. Areas subjected to airborne deposits of volcanic products, such as tuffs and ashes, can be very porous and form effective pathways for waterborne radionuclides to the biosphere. Currently active volcanic regions cannot be regarded as suitably stable sites.

4.1.1.3 Faults and Other Geologic Structures

Detailed, high-quality geologic maps are required to establish where past movements have occurred and where future movements might take place. Three dimensional geologic data are necessary for engineering purposes, but, in obtaining these data, it is especially important that the integrity of the site not be jeopardized by exploration; the nondestructive character of certain geophysical measurement techniques is an important asset in this regard. Directions of principal stresses and the tensional or compressional character of the deviatorial stress can sometimes be inferred from the geometry and slip directions of the faults. Such data can be valuable because they allow comparison of the historical stress conditions with determinations of the present stress state, as discussed in the next section.

The geologic record of fault displacements and lengths in the region around the site can be used to estimate the maximum magnitude earthquake to be expected on active faults (see, for example, Smith 1976). In this way, the short historical record of earthquakes can be extended to geologic time intervals.

4.1.1.4 Ambient Stress Conditions, Rock Mass Stability

Experimental determination of the state of stress at any potential repository site is of primary importance in evaluating the site's safety and stability on at least five different counts.

First, although sites that are not prone to seismic or volcanic activity will be selected on geological and geophysical bases, it is advisable to assess specifically the geomechanical stability of a site in terms of the state of stress to which the rock at the site is subjected. This is necessary to ensure that neither pre-existing planes of weakness nor new fracture planes are likely to be mobilized, even in the presence of a full hydrostatic or lithostatic head of water, and also will provide a measure of the relative stability of the site, i.e., the proneness to instability due to the mechanical and thermal stress changes induced by the repository. The state of stress should be such that the resistance to slip (i.e., the product of the effective normal stress assuming a full hydrostatic head and the coefficient of sliding friction) is appreciably greater than the shear stress across planes of all orientations within the rock mass at the site.

Second, the minimum value of the normal stress across planes of all orientations within the rock mass at the site must be determined, and should exceed the pressure of the hydrostatic head of water. This will ensure that existing fractures are not fully opened and thus will have lower hydrologic transmissivity than they would at lower values of the normal stress.

Third, the stress states described above may still allow relatively great stress differences. In the absence of good data on the long-term strength of rock, it would seem prudent to place a conservative upper limit on the maximum permissible stress difference in the rock mass at the site. Potential fault movements at the site depend upon the ratio of the difference between the normal stresses and the effective normal stress on any rock surface. The effective stress is the normal stress less the hydrostatic pressure. To obviate the likelihood of faulting, especially in the presence of hydrostatic pressure, the difference between the values of the maximum and minimum components of the principal stresses should be small. Acceptable values for these components can be calculated in terms of Coulomb friction and effective stresses (Jaeger and Cook 1976).

Fourth, to ensure that stable openings can be made in the rock at the site and that these can be kept open for whatever length of time is considered necessary, some limit should be placed on the value of the maximum stress and on the stress difference in the rock mass at the position of the excavations. These values will be related to the strength and plasticity of the rock at the site, and the layout of the excavations.

Finally, the heat generated by the radioactive wastes will produce thermal stresses, and possibly thermal stress cracking, in the rock mass which may tend both to reduce the stability of the mass and increase its permeability. The acceptability of these changes will depend on the pre-existing stress conditions and the details of the design of the repository.

4.1.1.5 Geothermal Gradients, Thermal Conductivity, and Heat Capacity

Regional data on the earth's heat flux are available (Lachenbruch and Sass 1977). Such data are obtained from measurements of the geothermal gradient, usually in drill holes, and the thermal conductivity, usually determined on samples in the laboratory. Detailed data of this kind are needed for engineering purposes and to establish base measurements before thermal sources are introduced. These data are indicative also of the tectonic character of the crust and, because of the low thermal diffusivity of rocks, provide measurable data on a geological time scale.

4.1.2. Geohydrologic Information

Although there are potential sites that may now be above the water table, it cannot be assumed that this condition for a particular site will always prevail in the future. Accordingly, it should be assumed that a repository may become saturated with water. The underground water system in the region of the repository is, therefore, of primary significance in determining the delay and release of radioactive materials from a repository for several reasons. Water moving through the repository and the surrounding geological media is generally considered to be the most probable transport mechanism for carrying radioactive materials to the biosphere. The groundwater velocity and the retardation factors for the predominate short-lived radionuclides must result in a transit time sufficiently long to allow the radioactivity of the nuclides to decay to harmless levels. The decay in radioactivity of longer-lived nuclides may be insignificant over these time periods, so the rate at which nuclides are carried from the repository to the biosphere, i.e., the total mass flux of dissolved nuclides, must be low enough to be harmless. The hydrologic regime will also affect geochemical reactions between the radioactive nuclides and the surrounding media, and any change in it around the repository will affect the mechanical stability of the repository.

Evaluation of the adequacy of a potential repository site will require careful measurement of the following geohydrologic factors: (a) directions, velocities, and quantities of regional groundwater flow; (b) hydraulic gradients, and velocities of water in rock joints; (c) fracture spacing, size, permeability, and porosity; (d) rock matrix porosity and permeability; (e) total water content of the rock mass; (f) changes in the hydrologic regime arising from repository construction and waste emplacement; (g) effects of transient geologic conditions on hydrology; (h) changes in the hydrologic pathways; and (i) metamorphism and metasomatism.

4.1.2.1 Directions, Velocities, and Quantities of Regional Groundwater Flow

The regional hydrologic flow pattern is critical to the long-term effectiveness of a radioactive waste repository.

The regional flow of groundwater is a transport mechanism that can move radioactive materials into the biosphere, but can also act to reduce the potential dose to man by volumetric dilution of the radioactive material. Flow of groundwater also brings radioactive materials into contact with solid particles in the aquifer/aquitard complex. If the radioactive material is sorbed by the aquifer solids, there will be a decrease in radioactivity in a down-gradient direction.

A subsurface hydrologic system includes three subsystems: (1) the recharge zone, (2) the transport zone, and (3) the discharge zone, with water flow from 1 to 2 to 3. Retention time and dilution will generally be greatest if the radioactive source (the repository) is in a recharge zone, and least if it is in a discharge zone.

Measurements of regional groundwater surfaces may allow adequate delineation of these zones in most geologic media, so that the general directions of present-day groundwater flow can, in many instances, be established with confidence. However, determination of the average velocities and quantities of flow becomes progressively more difficult with decreasing permeability of the geological media. Adequate numerical models exist for predicting the regional flow of groundwater once the needed parameters are obtained. However, the existing models are not necessarily adequate for predicting local flow patterns, especially in rocks with widely-spaced fractures or solution openings, or where rapid changes in water salinity or temperature, or both, become important.

4.1.2.2 Hydraulic Gradients and Velocities of Water in Rock Joints, Shears, and Faults

Fracture systems and cracks in the rock mass may produce a secondary permeability which is greater by several orders of magnitude than the intergranular permeability of the rock material itself. In rocks of low permeability, fractures become the most significant path for the flow of groundwater. Accordingly, careful investigation of the hydrologic properties of any fracture system, including thermal hydrofractures, will be a prerequisite to predicting whether or not the performance of a repository site will meet environmental radiation standards.

4.1.2.3 Spacing, Size, and Porosity of Fractures

Water moving through rocks of low porosity flows more rapidly than an equal volume per unit of time of water moving through a more porous granular medium, because the material of lower porosity can accommodate less fluid in a given volume. In most places, the more closely spaced the fractures, the higher the porosity, and hence, the larger the storage capability of the rock mass. If fractures are closely spaced and the fracture openings are large, the hydrology of the fractured rock will be similar to that of a granular material. Intense fracturing also exposes large surface areas of the geologic medium that may act as chemical retardants.

4.1.2.4 Rock Matrix Porosity and Permeability

The porosity and intrinsic permeability of the rocks surrounding the waste repository will control the fluid content of the rocks and will also influence the thermal regime in the vicinity of the repository. The long-term effects of metasomatism must be considered.

4.1.2.5 Total Water Content

Even rocks of very low porosity will contain some water, at least within the range of depths considered for a repository (Van Zigl 1976). The specific water content of the rock and the hydrous phases in it, and the chemical properties of the aqueous medium (see Section 4.1.3) will be important in calculating the potential for leaching the solidified wastes and the overpack material, and the degree to which certain subsequent chemical reactions may occur.

4.1.2.6 Changes in Hydrologic Properties Related to Repository Construction and Waste Emplacement

Changes in the hydrologic properties of the rock mass and the groundwater flow pattern that will occur during and after construction of the repository should be determined. Construction will change the hydraulic gradient and increase the density of fracture in the vicinity of the repository, producing a large short-term impact on the local hydrologic regime. To assess these short-term changes reliably, in situ data need to be gathered at the site during and after excavation of the repository.

The effect of the access shaft on the local flow pattern will be particularly important because the shaft could become a short circuit for flow to the biosphere once the repository becomes full of water.

The longer-term effects of thermal changes resulting from the heat generated in the repository should also be evaluated. For example, increasing the temperature from 25°C to 100°C will reduce the viscosity of water by a factor of more than three. Assuming that other factors remain constant, such a change would increase the flow rate by a corresponding factor, because the flow rate is inversely proportional to the viscosity of the fluid. Such an increase in temperature will also lower the density several percent or raise the pressure. Heated water will tend to rise, setting up convective flow cells in the vicinity of the repository, which will be superimposed on the regional flow system, and may also increase the reaction rates, including metasomatism, which changes the rock composition.

4.1.2.7 Hydrologic Effects of Transient Geologic Conditions

If a repository is sufficiently deep, transient events such as meteorite impact and erosion will not significantly affect the hydrologic system in the vicinity of the repository over a relatively short geologic period (thousands of years). Earthquakes could suddenly change the fracture patterns and, hence, the flow patterns. However, over many thousands of years, a number of events could take place to change substantially the hydrologic regime. These include: (a) climatic changes--an increase in rainfall would probably accelerate the flow of groundwater; (b) tectonism--tilting of the ground surface could change (even reverse) the hydraulic gradients and thus alter the direction and velocity of flow; (c) erosion--which could lower the base level of streams and alter the hydraulic gradient, and could possibly expose aquifers, causing the groundwater to discharge at the surface; and (d) stream capture--another possible result of erosion or tilting.

The largest change of hydraulic potential could come from water under high pressure from a continental glacier. The basal water could have a head of more than 3,000 feet. Another drastic change could come from osmotic potentials developed by changes of water chemistry.

The significance of each of these, and similar events, must be evaluated for each potential site.

4.1.2.8 Changes in the Hydrologic Pathways

Careful evaluation of the items discussed in the last two sections will allow predictions of changes in the hydrologic pathways between the repository and the biosphere. A separate path-to-human beings scenario should be developed for each likely change in the hydrologic regime.

4.1.3. Geochemical Information

Transport of radionuclides from the repository to points of significant human access is a process that involves chemical interactions of fluids containing radioactive materials with geologic and overpack material. Analysis of this process, including chemical retardation of waste transport by the surrounding geologic media, is an essential step in confirming the adequacy of the repository. Effective analysis will require sufficient information to predict chemical transport of the radioactive substances, both within the geologic media as altered by the emplacement of wastes, and beyond the site to points of significant human access. Chemical redistribution of wastes and surrounding substances within the repository could accelerate the mobilization of radioactivity in the hydrologic regime. Chemical concentration or "focusing" of fissionable actinides could result in a criticality that could potentially affect adversely the future performance of a repository. For example, focusing could occur by formation of new complex molecules of the actinide elements and their chromatographic separation via ion exchange between percolating groundwater and surrounding mineral surfaces. Thus, geochemical transport over the short-distance scale of the repository itself, as well as the longer-distance scale between the repository and human beings, is of concern.

Important characteristics to be determined in the geochemical assurance of a repository site include the physical properties of the solid and fluid media, the composition of the media and wastes, the interactions between the wastes and solid medium, and the influence of temperature and pressure--especially on the dissolution and transport of the wastes away from the points of emplacement. In particular, the following factors need to be carefully evaluated: (a) hydrologic characteristics that may regulate chemical transport, (b) chemical characteristics of the fluid medium in the immediate vicinity of waste packages, (c) chemical characteristics of solid surfaces in the vicinity of the waste package, and (d) redox conditions, buffer systems, and chemical characteristics of the solid and fluid media on a large scale around the repository.

4.1.3.1 Hydrologic Characteristics that May Regulate Chemical Transport

These characteristics should be determined in relation to both small-scale effects between the waste package and the immediately surrounding media, and large-scale effects between the repository and points of significant human access.

In conceptual designs of repositories that have been described (KBS 1977), it has been assumed that the inflow of water toward emplaced wastes and flow between the wastes and aquifers will determine the rate of chemical dissolution and the transport of radioactivity as an aqueous solution to points of significant human access. Hydrologic characteristics may differ considerably in different geologic media. For example, bedded salt may contain significant amounts of aqueous brine in inclusions, in addition to the water held by intercalated clays. While they are not mobile through fissures in the undisturbed repository, the inclusions may become mobile in the presence of waste emplacements because of the thermal and chemical perturbations of the salt by the warm and dissolving wastes (Bredehoeft et al. 1978). Moreover, the fluid volume for a given amount of water in a mixed salt system depends on the content of dissolved waste elements as well as on constituents of the surrounding media, and may be determined by chemical phase relations as well as by the amount of water present per se. In the case of granite at low ambient rock temperature, the water contained in fissures may make up most of the aqueous flow around waste containers, although at elevated temperatures additional bound water in the rock and hydrous minerals may become mobilized. Since the geometric arrangement of fissures in crystalline rock is not in general isotropic, the rate of water inflow and chemical attack on the wastes may depend on emplacement orientation. On a larger scale, hydrologic transport of dissolved radioactive wastes to human beings may involve aqueous flow through geochemically dissimilar strata with differing ion exchange and other chemical properties that govern chemical transport rates. Therefore, the hydrologic characterization must be detailed enough to make predictions concerning chemical transport within the repository, in its immediate surroundings, and on a larger scale.

4.1.3.2 Chemical Characteristics of the Fluid Medium in the Immediate Vicinity of Waste Packages

These characteristics include: (a) concentrations of dissolved inorganic and organic substances, (b) stable and naturally-radioactive isotopic composition of key elements useful for estimating groundwater flow and history, (c) oxidation-reduction and acidity properties, and (d) potential for forming chemical complexes by interaction of waste substances with organic and inorganic agents.

Chemical characterization of the aqueous environment in the immediate vicinity of the waste packages should include not only the major inorganic ions routinely determined in groundwater, but all constituents that may affect the rates of solubilization and transport of radioactivity away from the points of emplacement. The objective of the characterization should be to assess the potential for forming chemical complexes and containing the radioactive elements that may control the rates of transport to points of significant human access.

The relevant properties and substances present that should be investigated will differ substantially among different geologic media, and in fact are not well understood at present. However, it is likely that both organic and inorganic dissolved groundwater constituents will affect chemical retardation of the transport of radioactive materials and should be investigated. The acidity and the ability of the fluid media to oxidize or reduce the waste elements may drastically alter solubility and mineral exchange properties during hydrologic transport, and must be thoroughly investigated. Certain key isotopic relationships of the naturally occurring constituents of groundwater may aid in verifying hydrologic transport models, and these should be determined. It is especially important to predict the chemical characteristics of the aqueous environment during the time of repository operation. Once the waste container begins to dissolve, these characteristics depend on both original composition of the groundwater and chemical substances added from the waste containers and any overpack material. In the case of bedded salt, it should be realized that the volume of aqueous phase present depends not only on the salt bed, but on phase relations between it and dissolved canister materials. The ability of crystalline rocks to retain radionuclides on mineral surfaces may be inhibited by ions liberated from dissolving canisters. Therefore, factors used in transport models to express the delay should be those measured for aqueous compositions representing the repository with its emplaced and dissolving wastes. It is emphasized that the waste form and container materials should be specified for particular geological media and sites for both near-term and long-term storage.

4.1.3.3 Chemical Characteristics of Solid Surfaces in the Vicinity of the Waste Package

These characteristics include: (a) the mineralogical matrix, (b) the fixed organic matrix, (c) susceptibility to chemical and physical alteration and radiolysis caused by the emplaced wastes, and (d) potential for interactions leading to enhanced corrosion and leaching of emplaced wastes.

If the waste canisters should begin to dissolve in groundwater, the efficacy of the geochemical barrier to migration of radioactive materials will depend on the chemical characteristics of solid surfaces in the vicinity of the waste package. Therefore these characteristics must be known. The mineralogical matrix determines retention by ion exchange between dissolved inorganic forms of radioactive elements and crystal surfaces. Such ion-exchange processes have been emphasized in recent research on waste isolation. In addition, however, most geologic aluminosilicate media contain a fixed organic matrix containing up to a few percent of carbon dispersed along grain boundaries. Much of the water movement is likely to take place in contact with the fixed organic carbon, and chemical retention of radioactive materials may be affected by the carbon matrix. As the temperature increases, the organic compounds degrade. While these compounds degrade in rather well known sequences, it is necessary to consider the effects of these degraded products on the wastes. Retention by both organic and inorganic components of the rock matrix should be determined by experiment. Moreover, the extent to which these fixed matrix components are altered by emplacement of the wastes must be carefully considered, including gradual radiolysis arising from radiation emitted during the repository lifetime which may affect chemical retention of dissolved wastes. In some repository designs there may be massive local alteration of the solid repository matrix during dissolution of waste canisters, and the chemical characteristics of the geologic barrier may be greatly modified. In the cases of both salt and crystalline rock, large amounts of divalent ions released by canister dissolution may replace much of the original coatings of the matrix surface with new substances and create a new chemical environment for migration of radionuclides. Such a possibility should be clearly foreseen so as to ensure that the retention efficiency of the barrier is correctly measured in all laboratory and field experiments for realistic repository conditions.

4.1.3.4 Chemical Characteristics of the Solid and Fluid Media On a Large Scale around the Repository

These characteristics include: (a) retention and delay of radionuclides on a large scale, i.e., around the repository, during their hydrologic transport to points of significant human access, (b) potential for large-scale change of the medium under imposed thermal gradients, (c) potential for large-scale change resulting from dissolution of waste packages, and (d) influence of biogenic interactions that may affect the mobilization of radioactive wastes and the rate of their transport to man.

Detailed knowledge is required of the large-scale transport of radioactive materials from the repository to the points of significant human access. If a transport model is used for the prediction, it should be based on knowledge, not only of local chemical exchange between the moving fluid phase and the rock matrix components, but of the resultant of many different exchange processes on a comprehensive scale. The model should be validated by field measurements that are scaled to represent the true chemical transport processes. The effect of thermal gradients on the transport should be accurately included in the field measurements, from the standpoint both of physical flow characteristics and of chemical gradients that may result from the imposed thermal stress. The chemical consequences of waste container dissolution on large-scale transport should be reliably assessed, such as the addition to the groundwater of large amounts of lead, if, for example, that material should be used as a shield for emplaced wastes against radiolysis of surrounding water or geologic media. Finally, biogenic interactions of the wastes--for instance, with bacteria and other living forms that concentrate or change the valence state of certain radioelements--should be considered and experimentally evaluated for their effect on the rate of migration of radioactive materials through the complete repository field to points of significant human access.

4.2 CONFIRMATION OF ADEQUATE ENGINEERING DESIGN

The preceding discussion has emphasized the geophysical, geohydrological, and geochemical factors that must be evaluated in confirming the general adequacy of a geologic region as a repository site, prior to site selection and excavation. Passing reference has been made to the influence of the excavation on some of these factors, but the importance of the engineering design, excavation, and sealing of the repository on the efficacy of waste isolation is major and warrants separate consideration.

The mechanical stability of underground openings depends on the relationship between the in situ stress conditions and the strength of the rock mass as influenced by the openings. The system of excavation should be designed so as to achieve maximum stability consistent with practicable operational design of the repository. Demonstration of this stability must include consideration of the following: (a) location and arrangement of excavation; (b) stresses and displacements induced by excavation; (c) support design; (d) location and arrangement of emplaced wastes; (e) temperature fields around canisters and around the repository; (f) thermomechanical stresses; (g) thermochemical stresses; (h) effects of temperature fields on hydrology; and (i) sealing (plugging) of shafts, boreholes, and tunnels.

The overriding requirements in this design process should be to provide an exceptional degree of safety and stability; designs that reduce uncertainties and risks and rely on easily demonstrable assumptions and calculations are justifiably preferable to others that may seem more economical.

4.2.1 Location and Arrangement of Excavations

Exploratory excavation at the repository horizon will reveal joints, faults, and other potential structural weaknesses in the rock mass, and will allow experimental assessment of in situ stress conditions, strength of the joints, and other weaknesses. It must be demonstrated quantitatively that the proposed location of the repository is tectonically very stable. The demonstration should take into account not only rock conditions within the repository, but also the effect of possible earthquake induced movements along existing faults within the region that may affect the repository. The excavations must be spatially oriented, in relation to each other and to structural features in the rock mass, so as to ensure maximum stability consistent with practicable operation of the repository.

4.2.2 Stresses and Displacements Induced by Excavation

The three-dimensional stress state and displacement fields induced by the geometry and layout of the excavations should be calculated as precisely as available procedures permit, taking into account the detailed structural features of the rock and rock stress conditions revealed by the exploratory excavation, as well as any uncertainties in the measured values. Calculation and measurement must demonstrate that the induced stresses and displacements are such that the mechanical stability of the system of excavations is everywhere well assured for a period significantly longer than that required for retrievability.

4.2.3 Support Design

To assure excavation stability over at least the period of retrievability, the rock mass in the immediate vicinity of the repository excavations may require artificial support or reinforcement. Calculations must clearly demonstrate that the support or reinforcement system is such as to ensure everywhere a highly stable condition of the rock mass, and such systems must not complicate the chemical system or at least not in unknown ways. Materials and methods used in the support system should be demonstrated to provide unimpaired support characteristics for a period significantly longer than that required for retrievability, and under the environmental conditions of a fully activated repository.

4.2.4 Location and Arrangement of Emplaced Wastes

Calculations must show that borehole receptacles for emplaced wastes are so placed that the thermally induced stresses will not impair significantly the stability of the rock mass, nor enhance its permeability. These calculations should include consideration of the possibility of communication between boreholes through pre-existing joints.

4.2.5 Temperature Fields

To a great extent, the waste storage capacity of an underground repository depends upon the ability of the rock around the emplaced wastes to withstand the temperature gradients necessary to allow the heat to flow away from the canisters. These temperature gradients change with time and with the heat flux; however, as long as the canisters release heat, gradients must exist around them to dissipate it. The calculations should include specific considerations of the temperature fields around the canisters and the repository.

The temperature gradients around each canister result in thermomechanical stresses. Such stresses may cause decrepitation of the borehole containing the canister, or the combined effect of many canisters may produce thermally induced fractures in the rock between the boreholes.

Over the longer term, the temperature of the rock mass in the vicinity of the whole repository will increase, giving rise to thermally induced stresses on a much larger scale than those associated with individual canisters. The interaction around the repository of temperature fields from each canister must be calculated. Where uncertainty exists as to the numerical values of the physical properties of the rock, sensitivity analyses should be carried out to illustrate the key variables and their significance.

Calculations of temperatures and thermally induced stress fields around individual canisters and amongst arrays of canisters will provide the information necessary to make critical decisions concerning maximum rock temperatures, maximum canister power, and the location and arrangement of the emplaced canisters.

4.2.6 Thermomechanical Stresses, Strains, and Displacements

Increase in temperature around the repository will induce compressive stresses in the rock within the heated zone and tensile stresses outside the zone. These stresses will be superimposed upon the pre-existing state of stress.

The distribution and intensity of these stress regions will vary with time. The effect of thermally induced stresses on the stability of the affected rock mass could be significant and should be calculated, taking into consideration such factors as the regional in situ stress conditions, and the orientation and stability of joints, fractures, and other discontinuities in the mass. The variation of stability throughout the lifetime of the repository must be calculated and shown to be acceptable under the most adverse thermal conditions generated. Thermally induced viscoelastic strains may affect retrievability over the short term in some media.

In the preferred design for a repository, the volume of the refilled excavations is likely to be so small relative to the remaining host material, that subsidence should not constitute a significant problem.

4.2.7 Thermochemical Effects

Temperatures and temperature gradients around canisters and in the repository may have important effects, particularly in the presence of water, on the dissolution, precipitation, and migration of elements and minerals toward or away from the canister. These processes are important in assessing the release and retention of radioactive materials, as discussed in Section 4.1.3.

4.2.8 Effects of Temperature Fields on Hydrology

As noted earlier in Section 4.1.2.6, the temperature changes induced in the rock may result in convection cells in the regional groundwater regime, thereby disturbing the pattern of groundwater flow. Calculations must demonstrate that the modified flow does not increase unacceptably the transport by water of radionuclides to the biosphere. Calculations must also demonstrate that any effects resulting from changes in temperature and pressure of water in joints do not cause unacceptable increases in the rate of movement of water along joints, and hence unacceptable changes of the induced stresses in the rock and in the stability of the joints.

4.2.9 Sealing of Shafts, Boreholes, and Tunnels

All man-made openings from the surface toward the repository tend to impair the isolation of the repository from the biosphere. Shafts from the surface into the repository, and boreholes that approach it, are potentially the most direct conduits for fluids and radioactive materials, even after careful sealing. Every effort should be made to ensure that isolation remains adequate, not only by sealing, but also in the original design of such penetration. The seal itself and the potential pathways in its vicinity should present both hydraulic and chemical barriers to the movement of radioactive materials comparable to those of the virgin rock mass. Experiments and calculations must demonstrate that measures taken to prevent movement of radioactive materials from the repository, both during waste emplacement and after sealing of all accessways, are such that these openings do not significantly reduce the overall integrity of the isolation.

4.3 CONFIRMATION OF ADEQUATE ENGINEERING DESIGN BY LARGE-SCALE OPERATIONS

The properties of subsurface media and their response to underground excavation and other perturbations are understood poorly by most engineering standards and requirements. Yet the minimum performance of an underground repository for radioactive wastes must be predictable with a high degree of confidence for time periods of unprecedented duration in terms of normal engineering experience. Consequently, an exceptionally cautious approach should be taken in demonstrating the adequacy and safety of any potential underground repository for radioactive wastes. Such an approach must include comprehensive, large-scale testing of representative lengths of the shafts, tunnels, and other components of the repository, under conditions as close to those prevailing at the actual repository as is practicable. Large-scale testing of this kind is done with three principal objectives.

First, it is necessary to provide measurements of the in situ properties of the geologic environment and of its response to underground excavation, under the conditions prevailing at the site of a repository and on a dimensional scale comparable to, or preferably the same as, that of the repository excavations themselves. This should eliminate or reduce to an acceptable level the scaling errors of the tests. Such tests are vitally important because of the difficulties and uncertainties in determining the conditions at a site (such as the state of stress, and the hydraulic pressure and gradients) and the properties of the rock mass (including the effects of geological discontinuities and the like), and of predicting what the response of the subsurface environment will be to excavation and other perturbations. The data gathered in such testing will provide both an indispensable check on earlier design predictions, and valuable new information with which to refine earlier designs and make further predictions with greater certainty than would otherwise be possible.

Second, it is necessary to demonstrate the appropriateness, and to measure actual effects, of the techniques to be used for making the repository, emplacing and, if necessary, retrieving the wastes, and, finally, for sealing the boreholes, shafts, and tunnels, after the wastes are committed to final disposal. It is particularly important to confirm, very early in the sequence of excavating, commissioning, and sealing a repository, whether or not the techniques proposed for each step are indeed both practicable and effective. These data should significantly reduce the uncertainties associated with earlier predictions of the performance and effects of the various techniques.

Third, precautions must be taken against omissions from the predictive models resulting from oversight or misjudgment. Predictions using theoretical or numerical models account for only those phenomena and effects that are known and are included, explicitly or implicitly, in the assumptions upon which these models are based. Large-scale testing provides an independent check on the models based on actual conditions found at the site.

4.3.1 Examples of Large-Scale Tests

For purposes of illustration, some of the kinds of tests envisaged are discussed below. It should be emphasized that the list is not exhaustive.

One of the most important operations that will need to be tested is the method by which the repository ultimately may be sealed. For this purpose, a shaft may be extended beyond the necessary depth by, say, about 50 m, to provide a representative length that can be sealed in the manner ultimately intended for the whole shaft. Other test lengths of shaft may be developed some distance from the actual shaft, at different depths below surface, from tunnels leading off the actual shaft. Also, at the depth of the repository, representative lengths of shafts and repository excavations should be sealed in exactly the same manner as is proposed for the corresponding excavations of the repository itself. Appropriate space should, however, be left between the blind ends of the test lengths of shafts and tunnels and the seals to allow water or gas to be pumped behind the seals for test purposes. The seals and the rock around them should be instrumented with mechanical and hydraulic transducers to measure their response to fluid pressures and rock stresses. These tests should begin as early in the construction of the repository as is practicable, to enable them to continue for a significant period of time. These tests should demonstrate the practicability and effectiveness of the techniques by which it is proposed to seal the repository, and the measurements should provide data sufficient to reduce significantly uncertainties in the predicted performance of the sealing methods.

The feature of an underground repository for disposal of radioactive wastes that differs most from civil and mining engineering experience of underground excavation is the thermal and radioactive loading of the excavations. Again, large-scale tests of the effects of thermal loading on the repository excavations should be made at the depth of the proposed repository, and at the earliest practicable opportunity. These tests can be done by installing electrical heaters and instrumentation over significant lengths of the tunnels in which it is intended ultimately to place canisters of wastes. Because of the low diffusivity of rock, it is desirable to schedule such tests so that a sufficient period of time is available to gather adequate test data before any actual wastes are emplaced. These tests should be thoroughly instrumented to measure the temperature fields and thermally induced stresses and displacements in the rock, as well as hydrologic and chemical effects. The data gathered from such testing are vital for certain elements of the repository's final design, e.g., choosing the maximum acceptable initial power output of waste canisters (for example, their age and composition at emplacement), and for reducing the uncertainties associated with earlier predictions.

Because the hydrologic behavior of a repository is so important for delaying the release and transport of radioactive materials, and because the effects of size on the hydrologic behavior of the subsurface environment are not well understood, a comprehensive set of large-scale hydrological tests is imperative. In addition to measurements made from boreholes, representative lengths of repository excavations at the depth of the proposed repository must be tested. Such tests may include careful measurements of the seepage of groundwater into the test length, and of the escape of fluid from test lengths subjected to suitable hydraulic or gas test pressures. Again, these tests should be scheduled early, so as to provide test data for as long as is practicable. The importance of these data in verifying in situ conditions and in reducing uncertainties in predictions based on modeling cannot be overstated.

Large-scale testing should also include measurements of the mechanical and hydrologic effects on the rock of the excavations and excavation methods, as well as tests of the proposed methods of rock reinforcement and ground support. Field tests should be conducted to determine the best ways of measuring in situ pore fluid pressures in the rock. Techniques are not well developed for making such measurements in relatively impermeable rocks. The measurements should be repeated over a period of months or years in order to be sure that static pressures have equilibrated after the disturbance of drilling the hole.

In addition to geomechanical and hydrologic testing of the kinds described above, full-scale tests of many operations and methods such as those for emplacing and, if necessary, retrieving the waste canisters must surely be regarded as good, and necessary, engineering practice.

Since geochemical retention of radioactive materials by the geologic environment is of central importance to the success of a repository, large-scale field testing of chemical transport models, parts of which have been based on laboratory-scale data, is essential. However, proper scaling of slow geochemical processes, so that appropriate field experiments may be conducted within a few decades or less, may present considerable practical difficulty. Because the Panel recognizes the formidable practical obstacles to such testing, it does not recommend here the specific large-scale geochemical measurements that should be made, but instead emphasizes the importance of attracting geochemical experts to direct substantial effort to this complex and crucial part of the large-scale field testing experimental program.

4.4 EXTRAORDINARY CONSIDERATIONS

Design and construction of most structures can normally be undertaken with considerable confidence based on accumulated experience and replication of information. Construction of repositories for radioactive wastes cannot be approached with such confidence. First, there have been few opportunities for collecting and especially for replicating data from potential repository sites; second, a far longer period of time is entailed than for any previous technology; third, the consequences of failure may be perceived to be greater than for most other structures; and finally, the accuracy and certainty of knowledge about subsurface phenomena is far less than in most other fields of scientific and technological enterprise. Therefore, certain extraordinary measures must be adopted to ensure that the process of assurance is adequate.

The assurance process outlined in this report depends centrally on the accuracy of the models used to predict the behavior of the repository. This accuracy depends upon the scientific validity of the models and the quality of the data used in them. Accordingly, four aspects of the assurance process--quality of the data, the extent and duration of measurement, credible modeling, and risk assessment and safety analysis--require extraordinary attention owing to the nature of the geological environment, the properties of radioactive wastes, and the public concern about this problem.

4.4.1 Quality of the Data

An essential requirement of the assurance procedure recommended by the Panel is a careful assessment of the uncertainties associated with all of the data. Where applicable, conventional methods for assuring the reliability of scientific data will be used. However, the experience and replication that is gained through the evolution of science and engineering practice is not fully available in the case of constructing and operating a waste repository. Therefore, a procedure should be devised to compensate for this important shortcoming.

Since the opportunities for gaining experience and for replication are limited to the few potential repository sites where excavation may be done, these sites should also be used to conduct experiments relevant to the repository's performance. One approach would be to have at least two groups working in parallel, independent of each other both in supervision and in source of financial support. One group would be directly engaged in the design, engineering, construction, and confirmation of an adequate waste repository, while the other would conduct independent and fundamental field investigations of the geologic environment. Because of the great importance of the repository program and the need to broaden our understanding of geologic conditions required for successful repository operations--especially if new repositories are to be constructed in the future--an independent and complementary investigation based on longer and broader range scientific objectives seems justified.

4.4.2 Measurement

A degree of uncertainty is associated with the accuracy and relevance of every measurement. The uncertainties arise from instrumental inaccuracy, time and spatial variations in the values of the quantities being measured, and random phenomena. To reduce these uncertainties and provide the information necessary for determining the statistical significance of any measurement, all measurements should be made at several different locations and repeated at intervals of time for an appropriate period. The extent and duration of measurement will depend on the properties of the phenomena involved. For example, subsurface media conditions vary from point to point and the time constants of transient conditions resulting from the perturbations caused by measurement techniques are relatively long. Therefore, most measurements must be made over periods of time ranging from several years to a few decades before they can be considered reliable. However, in some cases, e.g., measurement of the current virgin state of stress in rock, a fairly reliable measurement may be obtained in a relatively short period of time, even though the values may vary from point to point.

It is important to note that the intention of making measurements over a seemingly extended period is not to enable extrapolation of trends in measurements over periods of time related to the operational life of a repository. Rather, it is to establish an appropriate level of confidence in the measurements; extrapolation over the operational life of a repository is done with predictive models.

4.4.3 Modeling

The release and transport of radioactive materials from a waste repository to the biosphere can be quantitatively predicted in the long term <u>only</u> through the use of numerical models. Because of the complexity of the repository system and the long time scales for which predictions must be made, realistic modeling is a difficult and challenging task. The validity and accuracy of any model depends upon the extent to which it reproduces the chemical and physical processes involved. A premium must, therefore, be placed on obtaining an adequate understanding of these processes and phenomena through laboratory and field studies. The overriding goal should be to provide a model adequate to predict explicitly the rate of release of radioactive materials from a repository, and its associated uncertainty. For purposes of assuring compliance with environmental radiation standards, the best and most appropriate models must be used together with data pertaining to a particular site.

Models can also make significant contributions to assuring the performance of an underground repository in other ways. They can be used to establish bounds to values of certain parameters, thereby providing valuable constraints on what may otherwise be considered an intractable problem. Furthermore, sensitivity analyses can be used to gain an insight into the relative importance of different factors, and to identify those requiring the most careful scrutiny.

In interpreting the results of modeling, careful attention should be paid to four aspects of the modeling process: the adequacy of the model itself, the adequacy of the data, the uncertainty in the final results, and the confidence level in the predictions.

A diversity of approaches to modeling would be useful in assessing the adequacy of simulation techniques. For example, if several models using different simulation structures but an equivalent set of input data were to make similar predictions, confidence in the models would be enhanced. Data collection and model development should proceed concurrently, since there is an inevitable interaction between the two activities. Knowledge of certain data, for example, can guide the modeler in his choice of which phenomena must be included in the model. The results of simulation studies, in turn, may indicate which additional data are needed, as well as the relative degree of accuracy required in such measurements.

Uncertainties in model predictions result from both the uncertainties associated with the model itself and those associated with the input data. The analysis of these uncertainties is a crucial component in the assurance procedure recommended by the Panel (see Chapter 3). Comprehensive model validation to predict the long-term behavior of the repository and its geologic and geohydrologic environments may not be possible. Therefore, techniques, such as validating model components, and reducing or bounding the uncertainties of these components, will be essential.

Because of the complexity of the models, the calculations required for analyzing uncertainties can be lengthy and costly. To avoid significant waste of effort and computer time, a carefully-planned approach to this problem, possibly involving the development of new techniques, will be required.

Ideally, it would be desirable to test the comprehensive model predictions against events occurring in the "real world". For a repository, however, because of the long time scales involved, such testing is not feasible. An alternative to long-term testing is to model events that have occurred in the past. The Oklo natural fission reactor in Africa is one possibility, although it would probably be very difficult to model since many of the original conditions and parameters are unknown. Another possibility, assuming the underground conditions are known well enough, is to model the distribution of radionuclides resulting from underground nuclear tests. A third possibility is to model the distribution of radionuclides or non-radioactive elements in waters near ore deposits. Finally, it may be possible to devise experimental conditions that can be used to test the ability of a model, or parts of it, to make long-term predictions.

4.4.4 Risk Assessment and Safety Analysis

Although geologic sites for radioactive waste repositories will be chosen in areas where the probability of transient geologic events occurring is very low, there is always the possibility, given the long time scales involved, that these events will take place. Consequently, in evaluating the total risk to human beings from radioactive waste disposal after emplacement of the wastes in a repository, it is necessary to take into account not only conditions that are expected, that is, where the system is assumed to change either not at all or relatively slowly and predictably, but also natural or man-made disturbances such as earthquakes and glaciation, or the construction of dams and the drilling of wells, which could affect the performance of the repository.

The proper approach to the evaluation of the effects of these disturbances involves: (1) the identification of the mode of failure associated with them; (2) an estimation of the probability of such a disturbance occurring; and (3) an analysis of the consequences of such a disturbance.

In order to satisfy licensing requirements, nuclear power plants must undergo a safety analysis, the purpose of which is to identify the consequences of failure in various parts of the system. For those incidents that could lead to serious consequences, engineered safeguards are employed to reduce the risks. A safety analysis can be useful in identifying those repository designs that can best withstand the effects of transient geologic events. These designs might include the choice of waste form, canister, and overpack material as well as the geometric arrangements of tunnels and shafts and the spacing of canisters within the repository. Such engineered safeguards could lead to a significant improvement in overall safety.

CHAPTER 5

STATUS OF CURRENT KNOWLEDGE

The Panel recognizes that the data currently available are insufficient to implement the assurance procedure recommended above with the degree of certainty required, but the status of current knowledge gives no cause to suppose that deep geologic burial, given appropriate safeguards, cannot provide a practicable method for isolating radioactive wastes from the biosphere. An understanding of the current state of knowledge indicates that, although much is known, certain important questions must be answered before the adequate performance of a repository can be assured.

In this chapter, the state of knowledge of the geoengineering, geohydrological, and geochemical phenomena affecting the potential use of geologic sites as underground repositories, and the applicable mathematical modeling techniques to predict the long-term performance of a repository, are discussed.

5.1 GEOENGINEERING

There is a wealth of experience concerning underground excavation. The 24 countries of the Organization for Economic Cooperation and Development alone construct a total of some 50,000 km of tunnels (OECD 1970) each year, under virtually every kind of terrain to depths approaching 4 km. Some underground mines have been in operation for more than a century and many mines use excavations 50 or more years old.

However, the disposal of radioactive wastes involves three principal factors that lie outside the realm of mining experience. First and foremost, significant amounts of radioactive materials must not be allowed to escape from the repository to the biosphere. Second, containment of these wastes must be effective for long periods of time, unprecedented in mining experience. Third, radioactive decay of the wastes within the repository also generates heat, which gives rise to thermal stresses in the rock mass.

These three considerations impose stringent requirements on the stability of the rock mass and upon the two principal factors that determine this stability; namely, the virgin state of stress in the rock mass and the strength of the rock mass. Additional experimental research and development is needed to allow reliable determination of both of these factors for any particular site.

5.1.1 Virgin State of Stress in the Rock

The vertical component of the stress in rock usually has a value close to the weight of the overburden. Departures from this rule may occur in areas of uneven topography at depths that are shallow compared to the relief, or in and close to inclusions and intrusions of rock with mechanical properties or temperatures different from those of the surrounding rock. Attempts to measure the complete state of stress in rock at various locations and depths throughout the world indicate that the value of the horizontal components of the stress state ranges from about one-third to three times that of the vertical components. Several reasons why determination of the state of stress in rock is of primary importance in site selection and repository design are discussed in Chapter 4, Section 4.1.1.4.

Although various methods for determining the state of stress in a rock mass have been proposed and used, there is considerable uncertainty concerning the accuracy and reliability of all of them. This uncertainty arises primarily because the relationship between the measured effect and the rock stresses producing the effect is usually unknown to a greater or lesser degree. Also, most techniques are not well suited to use at depths greater than 10-50 m in a borehole. Hydraulic fracturing does not have the depth limitation, but procedures for interpretation of test results are still of uncertain validity. A concerted and sustained research effort is required to develop reliable techniques for determining rock stresses in situ at depth.

5.1.2 The Strength of Rock Around Excavations

Underground excavations can have many different configurations. The most important consideration in laying out the excavations for an underground repository of radioactive wastes is the safety, stability, and security of the excavations. In general, therefore, such excavations are likely to take the form of a series of adjacent but more or less independent tunnels. This design results in simple, safe excavations with a high degree of isolation between tunnels.

Laboratory measurements of the strengths of small intact specimens of rock and theoretical analyses of the stresses around tunnel-like excavations suggest that rock failure is not a significant problem. However, it is generally accepted that such a simple approach does not accord with reality. It neglects at least two important factors, namely the effects of size and of geologic structure on the strength of rock.

Size is thought to have a significant effect on the strength of geologic materials, but there is a dearth of quantitative data on this question. Most of the experimental information available (see Jaeger and Cook 1976) concerns more or less cubical specimens of coal. Evans and Pomeroy (1958) and Evans et al. (1961) quote a wide range of crushing strengths for cubes of coal: the smaller the cube, the greater its strength.

Very few data are available for hard rock. Pratt et al. (1972) obtained the results for laboratory and in situ specimens of quartz diorite, showing a pronounced effect of size on strength. Obert et al. (1946) and Hodgson and Cook (1970) found size to have little effect on strength. In general, it appears that brittle rocks containing fractures that increase in size with the specimen size should exhibit marked size/strength dependency, whereas others that are relatively free of fractures should exhibit little size/strength dependency. However, present data are not sufficient to prove this assertion. Most rocks can be expected to exhibit a decrease in strength with increase in size.

In practice, the behavior of rock around many excavations is determined by its structure and the presence of geologic discontinuities (Hoek 1977). However, little is to be gained in terms of a general, as distinct from a site-specific, attempt to evaluate this phenomenon. A worst-case analysis always results in rock failure and any less demanding theoretical assumptions, no matter how obscure they are, merely beg the questions concerning specific data on the frequency, character, orientation, and properties of such discontinuities.

Nevertheless, it is necessary to form some idea of the magnitude of the effects of size and of geologic discontinuities on the strength of hard rock in order to evaluate its potential as a location for an underground repository of radioactive wastes. Some guidance may be gained from an examination of the values of the field stresses known to have caused damage to tunnels in hard rock.

Cook (1975) studied tunnels in deep gold mines of the Witwatersrand System; these excavations had a square cross section about 3 m on a side, and were made in argillaceous and arenaceous sediments with laboratory uniaxial compressive strengths in the range 170-340 MPa (1.7-3.4 kilobars). Cook concluded that, in the tunnels studied, damage would start when the vertical (maximum) component of the field stress reached 50 MPa and would become dangerous at about 100 MPa. Ortlepp et al. (1975) adduced equivalent observations of the onset of damage to similar tunnels totaling many hundreds of meters in length, which may be interpreted as supporting Cook's conclusion.

In salt, the values of the maximum principal stresses and the maximum value of the differences between them (the virgin state of stress in salt is likely to tend towards a lithostatic condition) should be limited to a degree consistent with the strength and creep of the salt. The period for which excavations may have to remain open and the temperatures to which the salt may be subjected must be borne in mind (Bradshaw and McClain 1971, Starfield and McClain 1973, Wahi et al. 1977).

5.2 GEOHYDROLOGY

It is of fundamental importance to recognize that water occurs in all types of rocks down to the depths commonly suggested for radioactive waste repositories. Even rocks such as granite, shale, and salt contain some water at great depths. Because of this fact, it is generally agreed that groundwater is the most likely vehicle for transport of the emplaced wastes to the biosphere. Unfortunately, the very rocks which have been most widely considered as hosts for a waste repository are the rocks on which we have the least hydrologic data.

5.2.1 Porosity and Permeability

There have been few in situ measurements at depth of the porosity and permeability of most types of low-permeability rocks. Laboratory measurements have been made of most rock types, but the values obtained are not necessarily representative of the in situ values for these materials. For example, shale and salt tested in a laboratory may yield permeability values orders of magnitude higher when the sample is not confined than when it is placed under confining pressures equal to those experienced in the field.

Gloyna and Reynolds (1961) measured the permeability of rock salt from both bedded salt and salt domes in the laboratory, and found that it decreased by about one to three orders of magnitude when confining pressures were raised from 500 psi to 5,000 psi. However, much more field data are needed to determine in situ permeability of salt formations.

Young et al. (1964) measured the permeability of samples of argillaceous rocks under a variety of conditions. The samples of siltstone typically exhibited an order of magnitude or greater permeability when a sample was tested under atmospheric pressure than when a sample was tested under confining pressures ranging from 101-379 bars. The same authors observed a marked increase in the permeability of a siltstone sample when the temperature was increased--a change much larger than they calculated could be a result of only the viscosity change. They concluded that either the permeability of the siltstone increased with temperature or the viscosity of the water inclusions in the sample changed with temperature in an abnormal way. They further stated:

> The anomalous behavior has important consequences relative to the calculation of water flow rate at subsurface conditions, especially for argillaceous rocks. Permeability measurements, including our own, are normally made at or near room temperature, and the permeabilities are calculated using the viscosity of normal water. When these permeabilities are used later to calculate rates of water flow under subsurface conditions at higher temperatures, normal water viscosities are again used. This procedure could lead to a considerable error (Young et al. 1964).

Brace (1965) showed that the porosity of granites ranges from 0.001 to 0.01. However, the pore space may double as the rocks approach failure and become dilated (Brace et al. 1966).

> Since water expands by only about 20% when pressure is reduced by 10 kbars, doubling of the pore volume would more than be sufficient to reduce pore pressure in, say, a typical crystal rock to nearly zero.... Pore fluids in adjacent unstressed rock would tend to flow into the region of reduced pore pressure (Brace et al. 1966).

5.2.2 Field Tests of Permeability

Standard techniques for measuring in situ hydrologic properties of aquifers (such as pumping tests) will not be applicable in evaluating the properties of the low-permeability rocks under consideration as host material for radioactive waste repositories. Tracer tests and injection tests that isolate intervals of the borehole, such as those used to test foundations at dam sites, may be useful in testing the near-field permeability of some fine-grained rocks. However, flow rates in the media are likely to be so small that the results of these tests will be suspect.

In situ testing in large-scale excavations (see Chapter 4, Section 4.3) will provide much of the field data necessary for site-specific evaluation. Such testing must be an integral part of assuring whether or not an individual site will meet environmental radiation standards.

A method of reservoir evaluation called "pulse testing" (Johnson et al. 1966) may be applicable in rocks of low permeability. Such a technique may be useful in describing the hydrologic parameters in both the near field and the far field. If applicable, the method could also be used to describe qualitatively hydraulic communication across faults and between rock zones, and the direction and magnitude of fracture trends (Vela and McKinley 1970). This technique appears to be very promising and should be thoroughly evaluated for possible application in rocks of low permeability.

There is a definite need to develop new field techniques for directly or indirectly measuring the permeability of fine-grained rocks. Ideally, such techniques could be used without impairing the intregrity of the site.

5.2.3 Flow of Groundwater in Fractured Rocks

Studies of the effects of fractures on the flow of groundwater in crystalline rock masses have spanned many years (see, e.g., Ellis 1906). Although most of the fractures tend to close with depth, water is known to occur in many deep mines (more than 2,000 m deep). Major fault and fracture zones may carry water far below the normal range of circulation.

Given two rocks with the same permeability but different porosity, the rock of lower porosity will transmit a fluid faster than the one with higher porosity. This phenomenon occurs because there is less fluid volume to displace in the rock of lower porosity. From the standpoint of waste migration, then, an ideal host rock for disposal of radioactive wastes would be one with moderately high porosity and extremely low permeability.

Davis (1969) compiled data which show that chemical dissolution along fractures in dense rocks will increase the overall permeability of a rock mass by two to four orders of magnitude. Inasmuch as the widths of fractures are extremely important in determining the rate of groundwater flow (the flow is proportional to the width of the fracture to the third power), any process that increases the size of the fracture opening can dramatically increase the rate of flow through the rock mass.

Another phenomenon that could increase the size of the fracture opening is an increase in fluid pressure within the crack. Moderate pressure changes could occur from increases in recharge to the aquifer system. Much larger pressure changes could occur in the vicinity of the waste repository if temperatures were to rise substantially. Therefore, it is important to obtain data on the dilation and contraction of fractures in response to changes in fluid pressure and temperature.

Flow through cracks that are essentially closed has not been studied in detail, although field measurements have been made (Snow 1968a, 1968b). Davis (1966) has proposed the interesting hypothesis that the flow of water in these cracks may be initiated by mechanical pumping of the fluid through the cracks by earth tides. This phenomenon ought to be investigated more thoroughly.

5.2.4 Measurements of Fluid Potentials

Because the flow of groundwater is directly proportional to the hydraulic gradient, measurement of the in situ fluid potential will be critical in evaluating a repository site. Techniques for making such measurements are well developed for granular sedimentary rocks. However, different procedures will be required for measuring the fluid potential in the fine-grained rocks that may exist in a potential repository site. For example, when a hole is drilled into a fine-grained rock, the rock mass within the vicinity of the borehole will be disturbed by the drilling process and invaded by drilling fluids. Thus, the hydraulic head in the immediate vicinity of the borehole may be grossly distorted from its hydrostatic condition. In most cases it will probably take months, perhaps even years, for the fluid pressure to re-equilibrate. Consequently, monitoring of the potential site should be done over a long period of time to ensure that hydrostatic conditions have been measured; furthermore, the down-hole instruments (e.g., pressure transducers) must be very accurate and long-lived.

5.2.5 Osmotic Potential

If a site is selected in shale, or in other rocks such as salt that are bounded by shales, osmosis may be an important process in moving fluids through the subsurface. The general concept of shale acting as a semipermeable membrane was thoroughly evaluated by Berry (1959). Young and Low (1965) proved experimentally that osmosis through natural fine-grained rocks can occur. Turk et al. (1973) attributed the fracturing of shallow fine-grained lacustrine sediments to a similar process. The possible flow of water by osmosis could be a very important consideration if the repository site is in bedded salt, because osmotic potentials depend upon a salinity contrast on either side of the semipermeable membrane. To date, osmotic potentials have not been measured in the field.

5.2.6 Rates of Dissolution of Salt

Several preliminary studies of the natural dissolution of salt have been done in the past several years, but most of them have been theoretical. Substantial amounts of additional research on in situ salt dissolution must precede the emplacement of wastes in a salt repository. Even in a dry salt environment, the rates of dissolution must be calculated using a scenario that envisions a future climate with more rain, and the consequent increases in recharge and flow of groundwater.

5.2.7 Flow Models

Simulation models that describe and predict the flow of underground water are currently available. With appropriate modification, some of these models appear to be adequate for predicting the movement of fluid into, within, and out of a radioactive waste repository, assuming that enough field data are supplied to the model. However, currently available models cannot accurately describe species transport and energy transport (Witherspoon 1977).

5.2.8 Dating of Water

An alternative technique for describing the hydrologic system is radiometric dating, which can be used to determine the age of water in pores. Such measurements can be used to calculate the velocity of the water flow, assuming that the recharge point can be identified. Most dating of water has been by tritium and carbon-14 techniques; carbon isotopes are useful for dating waters as old as 40,000 years. It would be helpful if new techniques could be developed to date waters in the range of 40,000-1,000,000 years. Possible methods for dating waters more than 50,000 years old was a topic for discussion at a workshop held recently in Tucson, Arizona (Davis 1978). The uranium-238/uranium-234 isotope, chlorine-36, and krypton-81 methods appear to have some promise for such use.

One of the most important problems associated with radiometric dating of waters is in obtaining uncontaminated samples of adequate size for analysis. In rocks of low permeability, such as those that might be considered for siting a radioactive waste repository, extracting an adequate sample may not be possible.

5.3 GEOCHEMISTRY

Strategies for the isolation and containment of radioactive wastes in geologic repositories are based on (a) the ability of the waste form and containing vessel to resist chemical dissolution by corrosive agents in the geologic media, (b) the ability of the geologic media to contain the wastes in the event that the wastes undergo dissolution, and (c) the gradual decay of waste radioactivity with time. A number of recent reports (e.g., American Physical Society 1978, OECD 1977, U.S. DOE 1978) have concluded that present understanding of the stability of the canister and waste form is not sufficient to rely on these alone as the principal long-term barriers to release of radioactive materials.

The principal concern about the adequacy of a deep geologic repository involves the potential leakage of radionuclides from the repository to the biosphere. For the shorter-lived radionuclides, the delay introduced by the canister, engineered barriers, groundwater transit times, and retardation factors should be sufficient to ensure that their radioactivity has decreased to harmless levels before they enter the biosphere. For longer-lived radionuclides, it is most improbable that a time delay can be relied upon to ensure sufficient radioactive decay. In this case, the properties of the waste form and engineered barriers will have to be stringent enough, and the product of groundwater flux and nuclide concentration will have to be low enough, to ensure that the rate of release of these nuclides into the biosphere is harmless. The kinds of geochemical information needed to design a repository so as to assure the adequate performance of the geologic barrier have been discussed in Chapter 4, Section 4.1.3.

5.3.1 Time Scales

Two time scales are of interest in considering the performance of a radioactive waste repository. One is relatively near term, e.g., several centuries, during which fission products constitute most of the radioactivity in the wastes. The second is the longer term, which may extend to a million years or more, during which a number of actinide elements and their decay products, as well as a few fission products and other nuclides, are present in significant amounts (American Physical Society 1978).

Isolation during the near term may be feasible by selecting a suitable waste form such as some chemically resistant matrix. Additional shielding of the waste form by canisters (KBS 1977) has been proposed to delay eventual chemical breakdown of the wastes. Considerable research attention is being given to the problem of developing new materials more resistant to groundwater dissolution (National Research Council [in press]).

On the longer-term scale, eventual dissolution of the wastes has been assumed; thus, the geologic environment surrounding the repository has been proposed as the most important barrier against transport of remaining radioactive material to the biosphere. De Marsily et al. (1977) have discussed geologic and geochemical requirements for safe isolation of radioactive wastes in terrestrial areas, with an emphasis on the uncertainties associated with making long-term predictions of geologic events. Guillaume (1976) emphasized that transuranic elements present the most difficult long-term waste isolation problem. Although separating these elements from the shorter-lived fission products and disposing of the two groups separately has been proposed to simplify the problem, the transuranics may still present the most difficult disposal problem.

5.3.2 Geochemical Retardation of Waste Elements

In 1977, the Nuclear Energy Agency pointed out that "not very much is known about the geochemistry of transuranium elements, and the little we know is almost exclusively about plutonium" (OECD 1977). Since then our knowledge of transuranic element geochemistry has been increased through research (see, for example, the work of Fried et al. 1977 and Krugmann et al. 1978). However, as suggested by Meyer (1978), a rigorous prediction of the geochemical behavior of all the important radioactive waste elements during transport from a repository through rock, considering the probable change of geochemical conditions over time and along transport pathways, may require the experimental determination of a larger number of parameters than can be carried out in a reasonable length of time. In view of the multiplicity of geochemical effects that must be considered and the limited time and effort which probably can be expended on their investigation, new research approaches will be needed for predicting the behavior of complex geochemical systems.

To date, most research seems to have been directed to geochemical retardation mechanisms (Burkholder et al. 1977). Other processes of potential importance which likewise require investigation, such as the behavior of colloids, interaction of radionuclides with organic matter (Means et al. 1978) or microorganisms, and precipitation of new solid phases in the geologic media appear not to have received sufficient attention.

Another area that deserves further investigation is the natural chemistry of groundwater, which may be the principal medium for transporting radioactive wastes to the biosphere.

In a review of the literature for the Swedish KBS program, it was stated: "Our review...has provided no direct information on the natural chemistry of groundwater deep in granitic rock in plutonic masses in any area of the world" (Hagconsult AB 1977).

Before the satisfactory performance of a radioactive waste repository can be assured, the geochemical processes affecting that performance must be thoroughly understood. Because the feasibility of geologic repositories may rest in large part on the effective retardation of radionuclide transport through geologic media, there is an urgent need for better geochemical knowledge concerning this transport.

5.3.3 Criticality in a Repository

Consideration of criticality must be taken into account before the satisfactory performance of a waste repository can be assured. Fissionable nuclides may be present in considerable amounts in radioactive wastes emplaced in a repository. It is possible that geochemical processes could, at some future time, cause redistribution of these nuclides so as to form a critical mass and a nuclear chain reaction. Both Jenks, in an overview of a conference on waste/rock interactions (Pennsylvania State University 1977), and a panel of geologists who reviewed waste isolation from an earth science perspective (U.S. EPA 1978) have mentioned the possibility of criticality.

A principal emphasis in repository design has been on limiting the long-term dispersion and migration of radionuclides over the considerable distances from the repository to the biosphere, whereas geochemical processes which could possibly result in criticality would more likely be confined to the vicinity of the repository itself. The possibility of such criticality must depend in part upon the design of the repository and upon the composition and form of the wastes to be emplaced. In a repository with individual canisters of solid waste emplaced in holes in rock, with a considerable amount of rock separating each hole, criticality would apparently require the intrusion of relatively pure water, the complete deterioration of the waste form, and the selective segregation of the contained plutonium into a critically favored geometry with plutonium suspended and dispersed in the optimum plutonium-water ratio for criticality. Behrenz and Hannerz (1978) have analyzed the possibility of such criticality for spent fuel in crystalline rock and have concluded that such events are extremely unlikely. Calculations (Allen 1978) indicate that such criticality could not occur from the contents of a spent-fuel canister in a mined salt repository, because of neutron poisoning from NaCl in such saturated brine. There is even less plutonium available for criticality in radioactive wastes from fuel processing.

However, for an entirely different kind of repository, such as a conceptual design in which waste equivalent to the waste contained in many canisters might be dumped into a single relatively large and deep hole in rock, there could be a greater possibility of accumulation and segregation of a critical mass of transuranic elements.

Criticality itself would not necessarily damage the repository and its containment, although this remains to be analyzed. The few experiences with inadvertent criticality in reprocessing operations indicate a short duration thermal pulse of much smaller magnitude than the longer-term thermal pulse from the radioactive decay of the wastes. Repetititve thermal pulsing from repeated criticality and self-termination might also occur. In analyzing the possibility of long-term criticality in a radioactive waste repository and the consequences therefrom, the effects of the thermal and pressure pulses upon the surrounding rocks, as well as the transmutation of the fissioning actinides into the short-lived fission produces should be considered.

The natural criticality event that occurred at the location of the present Oklo mine in Gabon, Africa, 1700 million years ago (Cowan 1976, Walton and Cowan 1975), illustrates that criticality events may occur in deposits of fissile nuclides as a result of geochemical redistribution processes. In this case many of the radioactive products of the fission event, including bred plutonium, were retained by the geologic formation. However, water soluble and volatile fission products were lost, including strontium-90, cesium-137, and iodine-129.

5.3.4 Overview

In order to obtain a proper appreciation of the various design features of a repository and their interactions, which must be optimized, it is best to consider in detail a complete waste disposal plan. In 1977, the electric power industry in Sweden presented a complete plan for disposal of high-level vitrified waste (KBS 1977); this plan was published for evaluation by scientific experts and the general public. An analysis of the plan (Rydberg and Winchester 1978) identified a number of areas where our present state of knowledge was not considered adequate to assure long-term safety; among the most important limitations cited were the geochemical uncertainties. Additional analyses of the plan by experts within Sweden have been summarized (Swedish Energy Commission 1978); furthermore, analyses by experts in several countries outside of Sweden have been published (Swedish Industry

Department 1978), and the recommendations of all reviews have been compared (Johansson and Steen 1978).

The geochemical requirements for a successful waste repository are stringent. Yet, much less is known about the geochemical processes that could affect the performance of a repository than about the relevant geophysical processes. Because geochemistry is a small scientific field, it appears that few geochemists have studied the problem and presented their findings. Consequently, some of the recent reports concerning the geologic concept of waste isolation have mentioned only briefly the geochemical aspects of the problem. Others that address these aspects more fully should be given careful attention: e.g., Angino (1977), Bredehoeft et al. (1978), Carter (1978), de Marsily et al. (1977), Hagconsult AB (1977), OECD (1977), Pennsylvania State University (1977), Rydberg and Winchester (1978), and U.S. EPA (1978).

5.4 MODELING

In the absence of previous experience concerning the geologic isolation of radioactive wastes, mathematical modeling techniques must be used to predict the long-term performance of a repository and to assess the potential risks. To provide satisfactory confidence of the adequacy of these predictions and assessments, and the uncertainties involved with them, the mathematical models must be based upon a sound understanding of the chemical and physical phenomena involved.

A number of models has been used to simulate the release and transport of radioactive materials from a waste repository to the biosphere (see, e.g., Burkholder 1976, Burkholder et al. 1977, Cohen 1977, Hill and Grimwood 1978, Holdsworth et al. 1977, KBS 1977, A.D. Little, Inc. 1978). A critique of the work by Burkholder et al. (1977) and A.D. Little, Inc. (1978), and a discussion of modeling in general can be found in U.S. EPA (1978). Except for the Swedish work (KBS 1977), this modeling effort has concentrated on analyzing a natural environment representative of a large number of potential sites, rather than on simulating the behavior of a repository at a specific site.

Analyses of risk assessment have been conducted; see, for example, Claiborne and Gera (1974), Girardi et al. (1977), A.D. Little, Inc. (1978), and Logan and Berban (1978). The accuracy of risk assessment is directly proportional to the understanding of the phenomena involved, and to the adequacy of the models and data employed. The uncertainties involved with risk assessment can be bounded, and sensitivity analyses can be used to estimate the relative importance of these uncertainties. Some of the analyses mentioned are based on inadequate data; however, none of the conclusions drawn from these analyses precludes providing satisfactory assurance of long-term compliance with environmental standards. Such analyses will assist in developing a methodology and the framework for an adequate data base which can then be applied to site-specific risk assessments.

GLOSSARY[1]

absorbed dose: The amount of energy absorbed per unit mass of irradiated material. The special unit of absorbed dose is the rad.

absorption: See *sorption*.

actinide series: The series of elements beginning with actinium, element No. 89, and continuing through lawrencium, element No. 103, which together occupy one position in the periodic table. The series includes uranium, element No. 92, and all the man-made transuranium elements. The group is also referred to as the "actinides."

activity: The number of nuclear transformations occurring in a given quantitity of radioactive material over a unit of time; the unit of activity is the curie (Ci), which is equal to 3.7×10^{10} (37 billion) disintegrations per second.

adsorption: See *sorption*.

alpha-radiation: See *radiation*.

aquifer: A subsurface formation or geological unit containing sufficient saturated permeable material to yield significant quantities of water.

aquitard: A formation of low permeability that acts as a partial barrier and retards the movement of groundwater.

beta-radiation: See *radiation*.

biosphere: That part of the earth that contains life.

calcine: A powder or granular form of high-level solid wastes produced by evaporating and decomposing high-level liquid wastes at temperatures above 500°C.

chemical complex: The statistical association of two or more ions in solution. The independent components of the complex can exist independently in solution.

chromatographic separation: Separation of chemical compounds by selective adsorption on surfaces of adsorbent materials.

criticality: A set of physical conditions in which a nuclear chain reaction is self-sustaining. The principal variables influencing criticality include the amount of fissionable material, its distribution in space, and the presence or absence of neutrons and neutron absorbers, reflectors, and of moderators (materials, such as water, that slow down fast neutrons). The minimum amount of fissionable material that will sustain a chain reaction for specified values of these variables is referred to as a critical mass.

decrepitation: The breaking up or cracking of certain crystals upon heating.

fault: A planar or gently curved fracture in the earth's crust across which there has been relative displacement (see fracture).

fissile material: While sometimes used as a synonym for fissionable material, this term has also acquired a more restricted meaning, namely, any material fissionable by neutrons of all energies, including (and especially) thermal (slow) neutrons as well as fast neutrons; for example, uranium-235 and plutonium-239.

fission: The splitting of a heavy nucleus into two approximately equal parts (which are nuclei of lighter elements), accompanied by the release of a relatively large amount of energy and generally one or more neutrons. Fission can occur spontaneously, but usually is caused by nuclear absorption of neutrons, gamma-rays, or other particles.

fission products: The nuclei (fission fragments) formed by the fission of heavy elements, plus the nuclides formed by the radioactive decay of fission fragments.

fissionable material: Commonly used as a synonym for fissile material. The meaning of this term also has been extended to include material that can be fissioned by fast neutrons only, such as uranium-238. Sometimes used in nuclear reactor operations to mean fuel.

fracture: Breaks in solid rock along which displacements have not occurred (see fault).

fuel (nuclear, reactor): Fissionable material used as the source of power when placed in a critical arrangement in a nuclear reactor.

fuel reprocessing: Processing of irradiated (spent) nuclear reactor fuel to recover useful materials as separate products, usually by separation into plutonium, uranium, and fission products.

gamma-radiation: See radiation.

genetics: A branch of biology that deals with the heredity and variation of organisms and with the mechanisms by which these are effected.

geologic disposal: Confinement of radioactive wastes in deep geologic formations for the purpose of permanent isolation.

geologic formation: Any igneous, sedimentary, or metamorphic rock represented as a unit in geological mapping.

geothermal gradient: Change in temperature per unit distance in a specified direction.

groundwater: Water that exists or flows below the surface (within the zone of saturation).

high-level liquid wastes: The aqueous wastes resulting from the operation of the first-cycle extraction system, equivalent concentrated wastes from subsequent extraction cycles, or equivalent wastes from a process not using solvent extraction, in a facility for processing irradiated reactor fuels. This is the legal definition used by the U.S. DOE.

high-level solid wastes: High-level wastes that have been converted to solid form. For purposes of this report spent fuel pins are considered a potential solid waste form.

hydraulic conductivity: Ratio of water flux to driving force for viscous flow under saturated conditions of water in a porous medium.

hydraulic gradient: The change in head of water with unit distance in an aquifer at a given point and in a given direction. It is analogous to slope of the piezometric surface (see also hydraulic head).

hydraulic head: The height above a standard datum, or the "level" of the surface of a column of water that can be supported by the static pressure at a given point--as applied to groundwater ($V^2/2g$ term is not included).

hydrology: The science of the phenomena and of the distribution of the waters of the earth.

ion exchange: A chemical process involving the reversible interchange of various ions between a solution and a solid material, usually a plastic or a resin. It is used to separate and purify chemicals, such as fission products or rare earths in solution. This process also takes place with many minerals found in nature and ions in solution, such as in groundwater.

ionizing radiation: Any radiation displacing (directly or indirectly) electrons from atoms or molecules, thereby producing ions. Examples: alpha-, beta-, and gamma-radiation.

isotope: One of two or more atoms with the same atomic number (the same chemical element) but with different atomic weight. An equivalent statement is that the nuclei of the isotopes of a given element have the same number of protons but different numbers of neutrons. Isotopes usually have very nearly the same chemical properties, and most of the same physical properties, but may differ greatly in radioactive behavior (see nuclide).

joint: Fracture in rock, generally more or less vertical or transverse to bedding, along which no appreciable movement has occurred.

long-lived isotope: A radioactive nuclide that decays so slowly that a quantity of it will exist for an extended period; usually a radionuclide whose half-life is greater than three years.

man-rem (or person-rem): A unit to express the collective dose equivalent in a group of people in a population. It is the product of the average individual dose equivalent multiplied by the number of individuals in that population.

microseismic: Pertaining to, characteristic of, or produced by persistent feeble earth tremors due to natural causes such as winds or ocean waves.

neutron: A subatomic particle with zero electric charge, and with a mass nearly that of a hydrogen atom.

nuclide: A species of atom having a specific mass, atomic number, and nuclear energy state. These factors determine the other properties of the element, including its radioactivity (see isotope).

permeability: In hydrology, the capacity of a rock, sediment, or soil for transmitting fluids. Permeability depends on the size and shape of the pores, and how they are interconnected (see hydraulic conductivity).

pH: A measure of the acidity or alkalinity of a solution; neutral solution has a pH of 7; an acid has a pH of less than 7; a base or alkali has a pH of greater than 7.

plutonium: A heavy, radioactive, man-made, metallic element with atomic number 94. Its most important isotope is fissionable plutonium-239, produced by neutron irradiation of uranium-238. It is used in weapons and for reactor fuel.

porosity: The ratio of the total volume of interstices in a rock or soil to its total volume, usually expressed as a percentage.

rad (acronym for radiation absorbed dose): The special unit of absorbed dose of ionizing radiation. One rad equals the energy absorption of 100 ergs per gram of absorbing material.

radiation: The emission and propagation of energy through material or space by means of electromagnetic disturbances, which display both wave-like and particle-like behavior; in this context the "particles" are known as photons. Also, the energy so propagated. The term has been extended to include streams of fast-moving particles (alpha- and beta-particles, free neutrons, cosmic radiation, etc.). Nuclear radiation is that emitted from atomic nuclei in varius nuclear reactions, including neutrons and alpha-, beta-, and gamma-radiation. Alpha-particles are the nuclei of helium atoms (mass 4, charge +2) produced by radioactive alpha decay of certain radionuclides. Beta-particles are electrons emitted in the process of radioactive beta-decay by certain radionuclides. Gamma-radiation is a kind of high-frequency electromagnetic radiation similar to X-rays, produced by certain energetic radioactive reactions.

radiation standards: Numerical criteria established to prevent people from being exposed to unacceptably high doses of radiation. This report is concerned primarily with the assurance of a standard governing the release of radioactivity from high-level radioactive wastes buried in deep geologic formations.

radioactivity (often shortened to "activity"): The spontaneous decay or disintegration of an unstable nucleus.

radionuclide: A nuclide that is radioactive (see also nuclide).

rem (acronym for roentgen equivalent man): The special unit of dose equivalent radiation. One rem of the radiation under consideration produces the same biological effect as one rad of X rays.

roentgen (abbreviation R): A unit of exposure to ionizing radiation. It is that amount of gamma- or X rays required to produce ions carrying 1 electrostatic unit of electrical charge (either positive or negative) in 1 cubic centimeter of dry air under standard conditions.

seismic: Pertaining to, characteristic of, or produced by earthquakes or earth vibration.

soma: The whole of any organism except its germ cells.

somatic: Of, relating to, or affecting the soma as contrasted with reproductive or germ cells.

sorption: In chemistry and geochemistry, the general term for the retention of one substance by another by close-range chemical or physical forces. Absorption takes place within the pores of a granular or fibrous material. Adsorption takes place largely at the surface of a material or its particles.

spent fuel: Nuclear fuel that has been irradiated and subsequently removed from the reactor. It contains uranium, plutonium and other actinides, radioactive fission products, and other nuclides.

storage: Temporary isolation and retention of radioactive waste material in a manner designed to facilitate removal at a future time without significantly increasing the risk of radioactive contamination due to handling and/or retrieval. (Permanent isolation, as in a repository, is referred to as disposal, permanent storage, or non-retrievable storage.)

stress:

compressional stress: A stress that tends to push together the material on opposite sides of a real or imaginary plane.

deviatoric stress: A measure of the extent to which the sum of the principal stresses approaches zero.

normal stress: Component of stress perpendicular to a plane.

principal stresses: Intensities of stress (maximum, minimum, and intermediate) along each of three mutually perpendicular axes in terms of which any state of stress can be described.

shear stress: A stress causing or tending to cause two adjacent parts of a solid to slide past one another parallel to the plane of contact.

stress difference: The algebraic difference between the maximum and minimum principal stresses.

tensional stress: A normal stress that tends to pull apart the material on the opposite sides of a real or imaginary plane.

thermal conductivity: A measure of the ability of materials to conduct heat. The amount of heat passing through unit area in unit temperature gradient.

thermal diffusivity: Coefficient of thermal diffusion. A thermal property of matter, with the dimensions of area per unit time.

transuranium nuclide: A nuclide having an atomic number greater than that of uranium (i.e., greater than 92). The transuranium nuclides produced in largest amounts by operation of uranium-fueled nuclear power plants are isotopes of neptunium, plutonium, americium, and curium. Two examples are plutonium-239 (half-life = 24,390 years) and americium-241 (half-life = 458 years).

uranium: A radioactive element with the atomic number 92 and, as found in natural ores, an average atomic weight of approximately 238. The two principal natural isotopes are uranium-235 (0.7 percent of natural uranium), which is fissile, and uranium-238 (99.3 percent of natural uranium), which is fertile, i.e., may be converted to fissile plutonium-239 by neutron capture. Natural uranium also includes a minute weight fraction of uranium-234.

volcanic activity: Igneous action at the surface of the earth, in contradistinction to plutonic action which takes place beneath the surface.

waste/rock interaction: The physical and chemical interaction between the waste form and the geologic medium in which it is placed.

water table: The surface in an unconfined aquifer material along which the hydrostatic pressure is equal to atmospheric pressure; the theoretical water table is approximated by a surface connecting static water levels in shallow wells which penetrate an unconfined aquifer.

NOTE

1 Conventional metric units are used in many definitions. For SI equivalents, see U.S. Department of Commerce (1977).

REFERENCES

Allen, E.J. (1978) Crticality Analysis of Aggregations of Actinides from Commercial Nuclear Waste in Geological Storage. ORNL/TM/6458. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

American Physical Society (1978) Report of study group on nuclear fuel cycles and waste management. Reviews of Modern Physics 50 (Number 1):Part 11.

Angino, E.E. (1977) High-level and long-lived radioactive waste disposal. Science 198:885-890.

Behrenz, P. and K. Hannerz (1978) Criticality in a Spent Fuel Repository in Wet Crystalline Rock. Atom-1978-05-30. Stockholm: Karnbranslesakerhet.

Berry, F.A.F. (1959) Hydrodynamics and geochemistry of the Jurassic and Cretaceous systems in the San Juan Basin, northwestern New Mexico and southwestern Colorado. Stanford University. (Unpublished Ph.D. Dissertation)

Brace, W.F. (1965) Some new measurements of linear compressibility of rocks. Journal of Geophysical Research 70:391-398.

Brace, W.F., B.W. Paulding, Jr., and C. Scholz (1966) Dilatency in the fracture of crystalline rocks. Journal of Geophysical Research 71:3939-3953.

Bradshaw, R.L. and W.C. McClain, eds. (1971) Project Salt Vault: A Demonstration of the Disposal of High-Activity Solidified Wastes in Underground Salt Mines. ORNL-4555. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Bredehoeft, J.D., A.W. England, D.B. Stewart, N.J. Trask, and I.J. Winograd (1978) Geologic Disposal of High-level Radioactive Wastes - Earth Science Perspectives. U.S. Geologic Survey Circular 779. Arlington, Va.: Branch of Distribution, U.S. Geological Survey.

Burkholder, H.C. (1976) Management perspectives for nuclear fuel cycle wastes. Nuclear Waste Management and Transportation Quarterly Progress Report. January through March 1976. BNWL-2029. Richland, Wash.: Battelle Pacific Northwest Laboratory.

Burkholder, H.C., J.A. Stottlemeyer, and J.R. Raymond (1977) Safety assessment and geosphere transport methodology for the geologic isolation of nuclear waste materials. In Risk Analysis and Geologic Modeling in Relation to the Disposal of Radioactive Wastes into Geologic Formations. Proceedings of a joint OECD/NEA workshop, Ispra, Italy, May 23-27, 1977. Paris: Organisation for Economic Co-operation and Development.

Carter, L.J. (1978) Nuclear wastes: the science of geologic disposal seen as weak. Science 200:1135-1137.

Claiborne, H.D. and F. Gera (1974) Potential Containment-Failure Mechanism and their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico. ORNL-TM-3639. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Cohen, B.L. (1977) High-level radioactive waste from light water reactors. Reviews of Modern Physics 49(1).

Cook, N.G.W. (1975) The siting of mine tunnels and other factors affecting their layout and design. In Association of Mine Managers of South Africa, Papers and Discussions, 1972-73. Pages 167-198. South Africa: Chamber of Mines of South Africa.

Cowan, G.A. (1976) A natural fission reactor. Scientific American 235(1):36-47.

Davis, S.N. (1966) Initiation of ground-water flow in jointed limestone: National Speliological Society Bulletin 28:111-118.

Davis, S.N. (1969) Porosity and permeability of natural materials. Flow Through Porous Media, edited by R.J.M. de Wiest. New York: Academic Press.

Davis, S.N., editor (1978) Workshop on Dating Old Ground Water. Report of a workshop held at the University of Arizona under the auspices of the Office of Waste Isolation, Nuclear Division, Union Carbide Corporation. Oak Ridge, Tenn.: Office of Waste Isolation.

de Marsily, G., E. Ledoux, A. Barbreau, and J. Margat (1977) Nuclear waste disposal: Can the geologist guarantee isolation? Science 197:519-527.

Ellis, E.E. (1906) Occurrence of water in crystalline rocks: U.S. Geological Survey Water - Supply Paper 160. Pages 22-28. Arlington, Va.: Branch of Distribution, U.S. Geological Survey.

Evans, I. and C.D. Pomeroy (1958) The strength of cubes of coal in uniaxial compression. Mechanical Properties of Nonmetallic and Brittle Materials, edited by W.H. Walton. London: Butterworth and Company (Publishers) Ltd.

Evans, I., C.D. Pomeroy, and R. Berenbaum (1961) The compressive strength of coal. Colliere Engineering 38:75-80, 123-127, 172-178.

Fried, S., A.M. Friedman, R. Archer, and J. Hines (1977) Retention of plutonium and americium by rock. Science 196:1087-1089.

Girardi, F., G. Bertozzi, and M. D'Alessandro (1977) Long-term risk assessment of radioactive waste disposal in geologic formations. In Risk Analysis and Geologic Modeling in Relation to the Disposal of Radioactive Wastes into Geologic Formations. Proceedings of a joint OECD/NEA workshop, Ispra, Italy, May 23-27, 1977. Paris: Organisation for Economic Co-operation and Development.

Gloyna, E.F. and T.D. Reynolds (1961) Permeability measurements of rock salt. Journal of Geophysical Research 66:3913-3921.

Guillaume, B. (1976) Problemes poses par la presence d'elements transuraniens dans les dechets du retraitement des combustibles nucleaires. Bulletin d'Informations Scientifiques et Techniques du Commissariat a l'Energie Atomique 217:31-46.

Hagconsult AB (1977) Groundwater movements around a repository. KBS Technical Report 06. Stockholm: Karnsbranslesakerhet.

Hill, M.D. and P.D. Grimwood (1978) Preliminary Assessment of the Radiological Protection Aspects of Disposal of High-Level Waste in Geologic Formations. Report NRPB-R-69. United Kingdom: United Kingdom Radiological Protection Board.

Hodgson, K. and N.G.W. Cook (1970) The effects of size and stress gradient on the strength of rock. Pages 31-34, Proceedings of the Second Congress of the International Society of Rock Mechanics, September 21-26, 1970, Volume 2. Belgrade: International Society of Rock Mechanics.

Hoek, E. (1977) Structurally controlled instability in underground excavations. Energy Resources and Excavation Technology, edited by Fun-Den Wang and George B. Clark. Proceedings of the 18th U.S. Symposium on Rock Mechanics, June 22-24, 1977 in Golden Colorado. Golden, Colo.: Colorado School of Mines Press.

Holdsworth, T., D.F. Towse, D. Isherwood, T. Harvey, and R. Heckman (1977) Site Suitability Criteria for Solidified High Level Waste Repositories. Draft report performed by the Lawrence Livermore Laboratory under the direction of the U.S. NRC. Livermore, Calif: Lawrence Livermore Laboratory.

Jaeger, J.C. and N.G.W. Cook (1976) Fundamentals of Rock Mechanics. 2nd Edition. "A Halsted Press Book." New York: John Wiley and Sons, Inc.

Johansson, T.B. and P. Steen (1978) Karnkraftens Radioactiva Avfall: Infor Ringhals 3-Beslutet. Ds I 1978:35. Stockholm: Industridepartementet.

Johnson, C.R., R.A. Greenkorn, and E.G. Woods (1966) Pulse-testing: A new method for describing reservoir flow properties between wells. Journal of Petroleum Technology (December 1966):1599-1604.

Karnbranslesakerhet [KBS] (1977) Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste. Five Volumes. Stockholm: Karnbranslesakerhet.

Killough, G.G. and L.R. McKay (1976) A Methodology for Calculating Radiation Doses from Radioactivity Released to the Environment. ORNL-4992. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Krugmann, H., A.M. Friedman, and S. Fried (1978) Migration of plutonium in rock: Incorrect dispersion formula. Science 200:87-88.

Lachenbruch, A.H. and J.H. Sass (1977) Heat flow in the United States and the thermal regime of the crust. In The Earth's Crust, edited by John C. Heacock. American Geophysical Union Monograph 20:626-675.

Little, A.D., Inc. (1978) Technical Support for Radiation Standards for High-Level Radioactive Waste Management. Task Report to U.S. Environmental Protection Agency. Contract 68-01-4470. Cambridge, Mass.: Arthur D. Little, Inc.

Logan, S.E. and M.C. Berban (1978) Development and Application of a Risk Assessment Method for Radioactive Waste Management. EPA/520/6-78-005. Springfield, Va.: National Technical Information Service.

Means, J.L., D.A. Crerar, and J.O. Duguid (1978) Migration of radioactive wastes: Radioactive mobilization by complexing agents. Science 200(4349):1477-1481.

Meyer, R.E. (1978) Adsorption of Inorganic Materials on Clays and Rock Samples. January 1978 Monthly Progress Report. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

National Research Council (1978) The Criteria Needed to Determine the Suitability of Sites for Geological Storage or Disposal of High-Level Radioactive Wastes. Washington, D.C.: National Academy of Sciences.

National Research Council (In Press) Solidification of High-Level Radioactive Wastes. Washington, D.C.: National Academy of Sciences.

Obert, L., S.L. Windes, and W.I. Duvall (1946) Standardized tests for determining the physical properties of mine rock. U.S. Bureau of Mines Report Invest. 3891. Springfield, Va.: National Technical Information Service.

Organization for Economic Cooperation and Development (1970) Report on tunnelling demand, 1960-1980. In Advisory Conference on Tunnelling, June 22-26, 1970, Washington, D.C. Paris: Organisation for Economic Co-operation and Development.

Organization for Economic Cooperation and Development (1977) Objectives, Concepts and Strategies for the Management of Radioactive Waste Arising from Nuclear Power Programmmes. Report by a Group of Experts of the OECD Nuclear Energy Agency. Paris: Organisation for Economic Co-operation and Development.

Ortlepp, W.D., R.C. O'Ferrall More, and J.W. Wilson (1975) Support methods in tunnels. Pages 167-198, Association of Mine Mangers of South Africa, Papers and Discussions, 1972-73. South Africa: Chamber of Mines of South Africa.

Pennsylvania State University (1977) National Waste Terminal Storage Program. Conference on Waste-Rock Interactions, July 6-7, 1977. Y/OWI/SUP-77-14268. University Park, Penn.: Pennsylvania State University.

Pratt, H.R., A.D. Black, W.S. Brown, and W.F. Brace (1972) The effect of specimen size on the mechanical properties of unjointed diorite. International Journal of Rock Mechanics and Mineral Sciences 9:513-529.

Rydberg, J. and J.W. Winchester (1978) Disposal of High Active Nuclear Fuel Waste: A Critical Review of the Nuclear Fuel Safety (KBS) Project on Final Disposal of Vitrified High Active Nuclear Fuel Waste. Ds I 1978:17. Stockholm: Swedish Energy Commission (Industridedepartementet Energikommissionen).

Smith, S.W. (1976) Determination of maximum earthquake magnitude. Geophysical Research Letters 3(6):351-354.

Snow, D.T. (1968a) Fracture deformation and changes of permeability and storage upon changes of fluid pressure. In Geophysical and Geological Studies of the Relationships Between the Denver Earthquake and the Rocky Mountain Arsenal Well. Colorado School of Mines Quarterly Report 63(1) January 1968. Golden, Colo.: Colorado School of Mines Press.

Snow, D.T. (1968b) Hydraulic Characteristics of Fractured Metamorphic Rock of Front Range and Implications to the Rocky Mountain Arsenal Well. In Geophysical and Geological Studies of the Relationships Between the Denver Earthquake and the Rocky Mountain Arsenal Well. Colorado School of Mines Quarterly Report 63(1) January 1968. Golden, Colo.: Colorado School of Mines Press.

Starfield, A.M. and W.C. McClain (1973) Project Salt Vault: a case study in rock mechanics. International Journal of Rock Mechanics, Mineral Sciences and Geomechanical Abstracts 10:641-657.

Swedish Energy Commission (1978) Miljo effektor och risker vid utnyttjande av energi. Ds I 1978:27. Stockholm: Industridepartementet Energikommissionen.

Swedish Industry Department (1978) Report on Review Through Foreign Expertise of the Report: Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste. Report Ds I 1978:28. Stockholm: Industridepartementet.

Turk, L.J., S.N. Davis, and C.P. Bingham (1973) Hydrogeology of lacustrine sediments, Bonneville Salt Flats, Utah: Economic Geology 68:65-78.

U.S. Department of Commerce (1977) The International System of Units (SI). National Bureau of Standards Special Publication 330. CODEN:NBSMA6. Washington, D.C: U.S. Government Printing Office.

U.S. Department of Energy (1978) Report of Task Force for Review of Nuclear Waste Management. DOE/ER-0004/D. Washington, D.C.: U.S. Department of Energy, Directorate of Energy Research.

U.S. Environmental Protection Agency (1976a) Environmental Radiation Protection Requirements for Normal Operations of Activities in the Uranium Fuel Cycle. Page 163, Final Environmental Statement, Volume 1. EPA 520/4-76-016. Washington, D.C.: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (1976b) National Interim Primary Drinking Water Regulations. EPA-570/9-

76-003. Washington, D.C.: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (1978) State of Geological Knowledge Regarding Potential Transport of High-Level Radioactive Waste from Deep Contiental Repositories. Report of an ad hoc panel of earth scientists. EPA/520/4-78-004. Springfield, Va.: National Technical Information Service.

Van Zigl, J.S.V. (1976) Electrical studies of the deep crust in various tectonic provinces of South Africa. American Geophysical Union Monograph 20:470-500.

Vela, Saul and R.M. McKinley (1970) How areal heterogeneities affect pulse-test results. Journal of Petroleum Technology (June 1970):181-191.

Wahi, K.K., D.E. Maxwell, and R. Hofmann (1977) A Simulation of the Thermomechanical Response of Project Salt Vault. Report prepared by Science Applications, Incorporated under Subcontract 86Y-16519V with Union Carbide Corporation, Nuclear Division, under Contract No. W-7405-eng-26 with the U.S. Energy Research and Development Adminstration. Springfield, Va.: National Technical Information Service.

Walton, Jr., R.D. and G.A. Cowan (1975) Relevance of nuclide migration at OKLO to the problem of geologic storage of radioactive waste. Pages 499-508, Proceedings of a Symposium on the OKLO Phenomenon held in Libreville, June 23-27, 1975, sponsored by the International Atomic Energy Agency. Vienna: International Atomic Energy Agency.

Witherspoon, P.A., ed. (1977) Movement of fluids in largely impermeable rocks. In Summary Review of Workshop at the University of Texas at Austin, under the auspices of the Office of Waste Isolation, Nuclear Division, Union Carbide Corporation. Oak Ridge, Tenn.: Office of Waste Isolation.

Young, A. and P.F. Low (1965) Osmosis in argillaceous rocks: American Association of Petroleum Geologists Bulletin 49:1005-1007.

Young, A., P.F. Low, and A.S. McLatchie (1964) Permeability studies of argillaceous rock. Journal of Geophysical Research 69:4237-4245.