Open-File Report 80-1065

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

RATIONALE FOR GEOLOGIC ISOLATION OF HIGH-LEVEL RADIOACTIVE WASTE, AND ASSESSMENT OF THE SUITABILITY OF CRYSTALLINE ROCKS

By

Harry W. Smedes

FOREWORD

Shortly after this report was completed, President Carter announced (Presidential Policy Statement, February 12, 1980, The White House) a comprehensive radioactive waste management program. The overall objective of that program is to isolate existing and future radioactive waste from the biosphere and ensure that it pose no significant threat to public health. Specific steps to accomplish this objective, for high-level waste, include:

1. Provide an effective role for State and local governments in the development of the program.
2. Adoption of an interim planning strategy focused on the use of mined geologic repositories capable of accepting waste both from reprocessing and unreprocessed commercial spent fuel.
3. Maintaining safe interim storage of these wastes until repositories are available.
4. Improving existing Federal authorities and structures for regulating storage, transportation and disposal of radioactive waste.
5. Improve mechanisms to ensure that all aspects of the waste management program will be conducted with the fullest possible disclosure to and participation by the public and technical communities, consistent with the need to protect national security information.
6. Encourage and support international cooperative efforts which advance our technical capabilities and our understanding of waste management options which are consistent with our nonproliferation policy.

As part of this program, the U.S. Department of Energy is mounting an expanded and diversified program of geologic investigations whose immediate attention will be on research and development and on locating and characterizing a number of potential repository sites in a variety of different geologic environments, and with diverse rock types. When four or five sites have been evaluated and found potentially suitable, one or more will be selected for further development as a licensed full-scale repository.

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RATIONALE FOR GEOLOGIC ISOLATION OF HIGH-LEVEL RADIOACTIVE WASTE, AND ASSESSMENT OF THE SUITABILITY OF CRYSTALLINE ROCKS

By

Harry W. Smedes

INTRODUCTION

One of the more urgent issues facing the world today is that of safe containment of radioactive materials--during the life of nuclear reactors and, subsequently, during the milennia of hazardous life of the nuclear waste. Large quantities of high-level radioactive waste already exist that must be disposed of safely. This waste has been accumulating for more than 30 years from the military nuclear weapons programs and more recently from commercial power generation. Present efforts to solve the waste disposal problem are focused on the use of mined geologic repositories capable of accepting waste from the reprocessing of commercial spent fuel as well as unreprocessed spent fuel.

To date, bedded salt is the rock medium of principal interest and under most intensive study for consideration as a host rock for geologic containment and isolation of high-level radioactive waste. Recent evaluations of the problem have strongly recommended that (1) ". . . at least one demonstration facility should be developed in a medium other than salt, preferably granite, and thoroughly evaluated before the decision is made to develop a facility into a full repository." (Hebel, 1978, p. S108); (2) ". . . there is an urgent need to study specific repository sites in different geologic environments" (Interagency Review Group on Nuclear Waste Management Report to the President, 1978; hereafter referred to as the IRG Report); and (3) ". . . a range of geologic environments including a variety of host rocks. . . be examined for possible use as a first or subsequent repository." (IRG Report, 1978).

Although not stated in the reports cited above, there are several reasons why rocks other than salt are beginning to receive higher consideration as candidate hosts for waste containment. The background is as follows:

Current estimates (IRG Report, 1978) are that as many as three repositories may be required to handle the volume of waste generated by the year 2000, and that additional repositories will be needed at a projected rate of one about every 5-20 years after the year 2000. However, as studies progress, the volumes of potentially suitable salt and the number of suitable sites in salt are rapidly diminishing due to unanticipated resources conflicts and geologic problems in the rock. At the same time, the number and nature of previously unanticipated problems of physical and chemical stability of salt as a repository medium are rapidly increasing. These emerging problems and, especially, thermal instability, are also true for shale, which for several years had been the second choice as a repository medium.

In contrast, granite and other crystalline rocks have numerous favorable attributes. There are far greater potentially suitable volumes of these rocks, for they are the most abundant rock types in the upper part of the Earth's crust. They occur widespread in large and deep-seated homogeneous masses exposed at the surface in stable shield areas, in the cores of many mountain ranges, in broadly uplifted regions, and in the subsurface beneath all of the younger sedimentary rock cover which in many places is thin.

Compared with salt and shale, crystalline rocks have great physical strength, inherent mechanical stability, and predictable engineering characteristics that allow underground excavations to remain open for centures. The water content of these rocks is low. At the surface and at shallow depths the water occurs in a network of fractures. In many posttectonic crystalline rock masses, these fractures largely result from decompression, as the formerly deep-seated rock mass is exposed at the surface by erosion. The fractures develop at and near the surface, and propagate downward, in time. In such masses it is possible that the vertical and horizontal pressures at depths approximating those of the planned repositories (1,000 m or so) have prevented the formation of fractures, and that the rocks are virtually impermeable.

Crystalline rocks are composed of stable high-temperature silicate minerals and have good sorptive properties--intermediate between salt and shale. The quantity and ionic strength of any water present is usually low, thus minimizing corrosion rates and adverse effects on sorptive properties.

Large volumes of crystalline rocks occur in many palces which have low seismic and very low tectonic activity. These attributes will help insure that present favorable conditions will remain so during the hazardous life of the waste in its inexorably slow movement toward the biosphere.

Scope

The growth and volume of nuclear waste (from the nuclear weapons program and spent fuel from nuclear power reactors) has been accompanied by a growth in public concern over the problems associated with disposal of that waste.

This report summarizes the disposal objective to be met and the requisite geotechnical criteria to meet that objective; evaluates our present ability to determine whether certain criteria can be met and to predict whether they will continue to be met; discusses the consequences of failure to meet certain criteria; assesses what is known about how crystalline rocks meet those criteria; lists important gaps in our knowledge that presently preclude final assessment of suitability; and suggests priority research to fill those gaps. The report presents an elaboration of the above-stated behavior and suitability of crystalline rocks, and a rationale of site-selection in support of the recommended prompt and intensive study of granite and other crystalline rocks as potentially highly suitable candidate media for radioactive waste disposal.

An overview is presented on what the rocks are, where they are, and what the critical attributes are of various crystalline-rock terranes in the conterminous United States. This is intended to provide a basis to aid in selecting, first regions, and then sites within those regions, as candidate repository sites.

The contention is made that it is essential to begin to consider crystalline rocks, not only as genetic and chemical classes, but as rock masses--that is, terrane units considered in full context with the enclosing environment in which tectonic, seismic, and other conditions are superimposed on the rocks. Most of the existing data that are critical to the assessment of suitability for waste isolation are for the behavior and properties of classes of rock rather than rock masses. Much laboratory data exist from studies of granite and other crystalline rocks--as well as for salt, shale, anhydrite, etc. However, very little is known quantitatively about the in situ properties of large rock masses (of any rock type), and it is imperative that these data be gathered.

To the extent possible, crystalline rocks are compared with salt, shale, and basalt lava flows--the rock media presently receiving greatest emphasis and study for radioactive waste disposal.

Definition

The term "crystalline rocks" is grammatically and technically atrocious. However, it continues to be used widely in the literature and vocabulary of waste management and conveys meaning to many prople. Therefore, it is retained in this report. The term generally is used to refer to granitoid rocks such as granite and gneiss but commonly is extended--as in this report--to encompass a wider range in composition, such as granodiorite and gabbro, and in origin, such as Precambrian metavolcanic and other metamorphic rocks above greenschist facies.

Relation to Previous Studies

Much laboratory data on fundamental properties of crystalline rocks and their behavior under stress and temperature was acquired before nuclear power and waste were envisioned, and much continues to be acquired under programs unrelated to the nuclear fuel cycle. Reference books and papers in technical journals in the fields of geology, chemistry, physics, and engineering abound with such data. There is also voluminous literature that deals with research on specific aspects of the radioactive waste problem: the DOE (U.S. Department of Energy) and its predecessors, the AEC (U.S. Atomic Energy Commission) and the ERDA (U.S. Energy Research and Development Administration), funded a variety of studies that dealt with specific parts of the total picture of waste isolation in crystalline rocks, such as laboratory studies of the thermophysical properties of rocks, sorption measurements, theoretical studies of thermal loading, borehole geophysics, and borehole plugging (see, for example, Asher, 1978). All those data have relevance to the waste disposal problem--in their encyclopedic nature they constitute many of the bits and pieces which have yet to be assembled in a comprehensive program of waste disposal. It is beyond the scope and intent of this report to cite or summarize those studies.

In contrast, research directed toward the total problem of waste isolation in crystalline rocks is sparse and, with only a few exceptions (such as Ekren and others, 1974) deals with specific rock types at three specific DOE sites which were chosen for other reasons. Extensive exploration for pilot repositories has been underway in basalt lava flows at the Hanford Reservatio in Washington; granitic rock at the NTS (Nevada Test Site); and deeply buried and fractured gneiss and schist beneath the Savannah River Plant, in South Carolina. However, none of these DOE facilities was located with any consideration of its suitability for waste disposal (Hubbert, 1972), an issue which arose much later. The decision to explore for disposal sites at those facilities was for convenience and expedience[1] because the DOE had readily

[1]Reference to "convenience and expedience" is not intended as a derision. The specific reasons listed--though not geotechnical--may be legitimate considerations. For example, in a press release July 4, 1979, the GAO (Government Accounting Office) recommended to the Congress that first consideration for repository sites should be given to those existing, highly contaminated DOE sites (including the Idaho National Engineering Laboratory which presently has no exploration programs). These four sites contain 95 percent of the high-level nuclear waste in the country. Using such sites, if possible, would ". . . avoid contaminating any more areas of the United States with radioactivity." In October, the Congress passed a resolution advising the DOE to follow such a policy.

available facilities and personnel at hand, the land is Federally owned and restricted, large quantities of waste are generated there, and the idea of onsite waste disposal seemed to be socially and politically less sensitive than disposal at some other location.

Social and political attitidues of acceptability undoubtedly will vary from one recommended site to another and most likely will change, one way or another, with time. This aspect is not considered further in this report.

To help fill the need for an expanded program of site selection, the USGS (U.S. Geological Survey) and the DOE Office of Nuclear Waste Isolation (ONWI) are now formulating a nationwide research program of screening for environments with suitable multiple natural barriers. In addition to this emerging program, a USGS report by Ekren and others (1974) described geologic disposal in general, dealing with all major rock types including crystalline rocks. That report presented a conceptual statement of the rationale of selecting media and regions based on widely accepted criteria such as stability, seismicity, flooding, and permeability. That report has been cited and incorporated in other reports (such as Schneider and Platt, 1974, v. 2). Examination of the suitability specifically of granite and other crystalline rocks has been undertaken by the USGS for the past 2 years, partly through funding by the ERDA and the DOE. This report is in part a product of that program. In addition, ONWI has just completed a preliminary study (Murrie and Gates, 1979) of crystalline-rock terrane which complements this report.

The DOE/ONWI currently is funding the LBL (Lawrence Berkely Laboratory) to participate in a significant cooperative program with Sweden involving a study of the hydrological and structural effects anticipated from the repositories in granitic rocks by studying the rock mass at the Stripa Mine in Sweden (Witherspoon and Degerman, 1978). Primarily, it is a program of fracture-hydrology and of rock mechanics. Numerous technical reports covering specific aspects of that research have been published. On the basis of early results of these studies, the Swedish Geological Survey is making studies in granitic gneiss at several other sites.

The only reports to date which deal extensively with the use of crystalline rocks for waste repositories are those by Murrie and Gates (1979) and the LBL (1979). The former is a reconnaissance characterization and appraisal of major crystalline-rock terranes in the conterminous United States, based on literature surveys. The regions are ranked in terms of their relative suitability (for waste repositories) through the use of a rating system. The LBL report summarizes the proceedings of a symposium which dealt with an evaluation of state-of-the-art research needs and research priorities related to waste disposal in largely impermeable rocks--crystalline and argillaceous rocks. The symposium and proceedings are pervaded by the assumption that hydrologic flow through crystalline rocks at repository depths will be dominantly via fractures and that matrix permeability can essentially be disregarded. In the present report, this is considered to be an untested premise which requires thorough testing and evaluation as the first priority of research. In support of this stand, several important lines of evidence are presented which strongly suggest that in some granitic rocks in certain kinds of terrane, the flow at reasonable depths will be only via matrix permeability.

Acknowledgments

After reviewing extensive literature, participating in workshops, symposia, planning sessions, and discussing various aspects of the problem with scores of colleagues, it is not possible for me to be certain about which parts of this report are a rehash of other people's ideas and which, if any, are mine. I hope that this report will at least provide a different perspective of the combined ideas and concepts of all of us. I gained important insights from the following members of an advisory group which I convened to help formulate a USGS research program in crystalline rocks: Lindrith E. Cordell, Colores J. Gable, Samuel S. Goldich, Andrew Griscom, Walter W. Hays, Leonard Konikow, Fitzhugh T. Lee, Dennis W. O'Leary, Gary R. Olhoeft, Zell E. Peterman, Paul K. Sims, and Charles J. Zablocki. Among the many others with whom I had helpful discussions, I wish to thank especially James D. Byerlee, William L. Ellis, William Z. Savage, Kenneth Watson, William S. Twenhofel, and Mark D. Zoback, all of the USGS; Gene Simmons (MIT); Hugh Heard (LLL); Maura O'Brien and Paul A. Witherspoon (LBL); Gary Murrie (Dames and Moore, Cincinnati, Ohio); David T. Snow (consultant, Colorado Springs, Colo.); Otto Brotzen, Hans Carlsson, Roland Pusch, Ove Stephannson, Soren Sherman, Andrejz Olkiewicz (Sweden); John E. Gale (Canada); Pierre Vaubourg (France); and Akeo Fuwa, Takaaki Kashiwagi, and Noritaki Sato (Japan).

GEOLOGIC REQUIREMENTS FOR A REPOSITORY

Objective

The objective of geological disposal of high-level radioactive waste is to prevent that waste from reaching the biosphere in hazardous amounts by isolating the radionuclides and other toxic materials until they have diminished to safe levels. No one has yet agreed upon what these are.

Criteria which ensure that this objective will be met must take into account the size, shape, and engineering characteristics of the repository and the nature and volume of the waste as well as the properties of the host rock and its structural setting. Behavior of the host rock may, in turn, dictate some design parameters of the waste form (such as thermal output) and the repository (such as depth, and density of loading of waste).

Nature of a Repository

Present policy (pending full environmental review) calls for an interim strategy of repositories to be in mined excavations deep underground (IRG Report, 1978, p. 61). This brief summary of the current concept of a repository is adapted largely from Schneider and Platt (1974, v. 1). (See also, Draft Environmental Impact Statement on Management of Commercially Generated Radioactive Waste).

During the active life of a repository (while being filled with waste), there will be a restricted-use buffer zone on the land surface about 5 km in diameter. Centered within this zone will be a barrier zone of about 1 km within which the complex of buildings and surface waste-handling facilities will be located.

A vertical shaft will extend from the surface to the repository level(s), as deep as 1,000 m or more. The underground workings will consist of a system of nearly 100 km (Schneider and Platt, 1974) of tunnels, or rooms and pillars occupying some 2,000 acres.

The waste from offsite will be transported to a complex of buildings at the surface where the waste will be unloaded and lowered down the shaft to remote-control vehicles which will transport it via access tunnels (totaling more than 11 km) to a specific room or section of tunnel. There, each canister will be emplaced in holes previously drilled into the walls and, probably, the floor.

The canisters (about 3 by 0.32 m) will be packed in material that is highly sorptive, provides a sealant to act as a barrier against corrosion, ingress of water and escape of radionuclides, and provides some shielding of radiation and reduces effects of seismic shaking. The holes will be filled and covered with similar sealant. After each room or section of tunnel has received its full load of canisters, it will be sealed from other sections by a bulkhead, and will be backfilled.

When the entire underground complex has received its full load of canisters, the remaining open space and shaft will be tightly filled and the shaft permanently plugged. Instruments will monitor the sealed repository for some unspecified time, after which all surface structures will be removed.

Retrievability

In the event that some unforeseen condition, event, or reaction occurs that would jeopardize the safe isolation of the waste, it must be retrievable (IRG Report 1978, p. 83). As a compromise of cost and risk, the present plan to effect retrievability is by leaving the main shaft unsealed and unfilled "as long as desired"--perhaps for decades (p. 83).

Retrieval for economic purposes (for reprocessing in order to obtain plutonium and unfissioned uranium in the spent fuel) was rejected by the IRG report.

Characteristics of the Waste Form

As generally used today, the term "high-level waste" includes (1) chemically reprocessed waste and (2) nonreprocessed spent fuels.

1. Until 1977, commercial and military high-level wastes were to be chemically dissolved, and some U and Pu removed (reclaimed). After 5 years, those reprocessed liquid high-level wastes were required[2] to be converted to a dry solid.

A number of forms of the solid waste have been and presently are being considered (summarized by Cohen, 1977), of which, a borosilicate glass and a glass ceramic currently are favored (IRG Report, 1978). The solid waste form will be composed of about one-fourth waste and three-fourths inert material--the glass or ceramic (American Physical Society, *in* Reviews of Modern Physics, 1978, p. F-107).

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[2]These regulations, by the NRC (Nuclear Regulatory Commission, U.S. Government, 1971) define high-level liquid waste as " . . . those aqueous wastes resulting from the operation of the first-cycle solvent-extraction system, or equivalent, and the concentrated waste from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuels."

2. In 1977, President Carter established a policy deferring indefinitely the reprocessing of nuclear waste. Therefore, during the life of this policy, any waste to be stored or placed in a permanent repository will consist of "raw" fuel assemblies (an array of spent-fuel rods and the cladding) chopped up so that each spent-fuel assembly will fit into one canister of the same general size and character as those required for the reprocessed waste. Because of differences among sizes of assemblies (depending on the type of reactor) the canisters arriving at the repository may be of several sizes (Koplik, Pentz, and Talbot, 1979, v. 2, p. 6). Either waste form is required to be ". . . chemically, thermally, and radiolytically stable . . . through a minimum of 90 days after receipt . . . at the Federal repository." (U.S. Government, Code of Federal Regulations, title 10, pt. 50, app. F, 1971).

All of the solid waste forms contain radioactive fission products and actinides; as a result they emit ionizing radiation, much of which is converted to heat within the waste mass. All forms are characterized by high levels of radiation, dose rate, heat output, and chemical toxicity. These data are summarized by Schneider and Platt (1974, v. 1, p. 2.14-2.16). Because the high-level liquid waste could be solidified immediately or could be stored for as long as 5 years before solidification, levels of chemical activity, heat output, and radiation for newly solidified wastes could range widely (Blomeke and others, 1974).

The various nuclides that constitute the waste, including those from cladding; fission products; uranium, thorium, and plutonium fuel wastes; and the transplutonium nuclides are listed in table 1.

Because of large differences in the rate of decay of radiation and consequent heat, the most significant nuclides in 100-yr-old waste will be Sr-90 and CS-137. These will have diminished to such low levels that they will produce virtually no heat by the time the waste is 1,000 years old. Various nuclides of Am and Pu will be the dominant heat-producers during the period of 1,000 to 10,000 years, after which daughter products of uranium will be the dominant heat producers (Schneider and Platt, 1974).

The solid waste would be encapsulated in canisters designed to provide maximum heat and radiation shielding and safety against accidents during its transport, and resistance to corrosion. The assumed standard canister of waste is a cylinder of stainless steel approximately 3 m long and 0.30 m in diameter (U.S. Department of Energy, 1979, p. 4.4). Larger ones will be required for some types of spent-fuel assemblies (Koplik and others, 1979, v. 2, p. 2.6).

After an assumed temporary storage of 10 years for partial cooling, the canisters are to be emplaced in the repository. At that time, one reference canister of spent fuel will have thermal power of about 0.19-0.55 KW, whereas a reference canister of solidified reprocessed HLW (high-level waste) will have thermal power of 2.3-3.2 KW (Koplik and others, 1979, v. 3, p. 2.4).

The skin (surface) temperature of the reference canister of 10-yr-old reprocessed HLW with thermal power of 3.2 KW is calculated as being about 460°F (240°C). One foot away from the surface of the canister the temperature [of salt] will be about 355°F (180°C). Temperatures of spent-fuel canisters would be proportionately less (below 100°C). Although these data are calculated for a canister emplaced in salt (Koplik and others, 1979, v. 3, p. 2.14), the temperatures would be at least as high for major crystalline rocks because of their lower heat conductivity (from data in Koplik and others, 1979).

If the temperature of HLW canisters should result in chemical and physical problems in the rock nearest the canister--as it certainly would in shale and, perhaps, in salt--the temperature could be reduced by further diluting the waste form. If the total thermal load should result in problems, the spacing between canisters could be increased. Either of these measures will result in an increase in either the number or the size of repositories needed (and an overall increase in the cost of waste disposal).

Table 1.--*Nuclides present in various fractions of solidified high-level waste (from Schneider and Platt, 1974, v. 1, app. 2.8.1)*

Cladding	Mn-54
	Fe-55
	Cu-58
	Cu-60
	Ni-63
	Ni-59
	Zr-93
	Zr-95
	Nb-95
Fission Product	Se-79
	Kr-85
	Sr-89, Y-90
	Zr-93
	Zr-95
	Nb-95
	Tc-99
	Ru-103, Rh-103M
	Ru-106, Rh-106
	Pd-107
	Sb-125, Te-125M
	Sn-126
	I-129
	Cs-134
	Cs-135
	Cs-137, Ba-137M
	Ce-144, Pr-144
	Pm-147
	Sm-151
	Eu-152
	Eu-154
	Eu-155
	Ho-166
U+Th Fuel Waste	Th-228 Chain
	Th-232
	U-232
	U-233 Chain
	U-234 Chain
	U-235 Chain
	U-236
	U-238
Pu Fuel Waste	U-234 Chain[1]
	U-235 Chain[1]
	U-236
	Pu-238
	Pu-239
	Pu-240
	Pu-241
	Am-241
	Pu-242
Trans Pu	U-233 Chain[1]
	U-234 Chain[1]
	U-235 Chain[1]
	U-236[1]
	Np-237
	Pu-238[1]
	Pu-239[1]
	Pu-240[1]
	Am-241
	Am-243
	Cm-242
	Cm-243
	Cm-244
	Am-242M
	Cm-245
	Cm-246
	Cm-247
	Cm-248

[1]Grows in after reprocessing.

Anticipated Volume of Waste

As of December 1978, there were 70 nuclear reactors on line in the conterminous United States (Burwell and others, 1979). The amount of waste produced by a reactor generally is cited in terms of an "average" 1 GWe (1 million watts) reactor with an average life of 25 years. Each of these "average" reactors will yield approximately 14,700 "typical canisters" of reprocessed solidified waste in the 25-year lifetime. Many more would be produced if reprocessing continues to be prohibited.

Projections of nuclear-power generation range widely and change over short periods of time in response to changes in actual rates. Current projections[3] indicate that nuclear-power generation in the year 2000 will be between 148 and 380 GWe. The inventory of all HLW (calculated as solidified waste) as of 1977, was about 173,000 m^3; that projected as the cumulative total to 1985, is about 310,000 m^3; and to 2000 is over 1 million m^3.

As large as they are, these projected volumes of waste (above) are much smaller than those which will have to be accommodated in a repository. The waste makes up only a small part of the volume of a repository, the bulk of which will be rooms, pillars, access tunnels, and the rock mass separating the canisters from one another.

Reprocessing would reduce the volume of waste to be emplaced in a repository.[4] The volume of spent-fuel assemblies and their cladding will not be reduced at all. As a result, more canisters of spent fuel will be required to contain an equivalent amount of reprocessed waste. However, the canisters of spent fuel can be more densely loaded in the repository. The latest estimates are that a repository which contains only spent fuel will require 20-100 percent greater area than one dedicated entirely to reprocessed HLW (Koplik and others, v. 2, 1979, p. 2-11).

Size and Number of Repositories

The size of an "average" repository in salt is cited as being 2,000 acres; a size that is thought to be reasonably achievable. By taking into account the heat conductivity and stress due to thermal expansion of salt rock (IRG Report, 1978, p. 7-11) an optimal thermal load of 120 MWe per 2,000 acres was calculated. This would permit the loading of about 35,500 canisters of current design. Adjusting for the different thermal properties of granitic rocks (IRG Report, 1978, p. 11), I conclude that a corresponding "average" repository in granitic rocks would need to be either about 85 percent larger--about 3,700 acres--or the density of canister loading would need to be about 44 percent less--about 20,000 canisters.

If all the waste were to be reprocessed (HLW) the predicted volume of this waste through the year 2005 is 35,300 canisters (Koplik and others, 1979, v. 2, p. 2.8-2.9). This is about the quantity considered for one "average" repository of 2,000 acres of salt. If, instead, all the waste is assumed to be in the form of spent fuel, there would be 196,000 canisters (Koplik and others, 1979, v. 2, p. 2.8-2.9) requiring twice the repository acreage, or twice the number of repositories. The total thermal energy of the two formats would be approximately equal.

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[3]These are averages of the conservative or "low case" and the liberal or "high case" strategies and include commercial and defense waste described in the IRG Report (1978, p. 4-10).

[4]In general, the waste resulting from 1-year's operation of a typical 1 GWe reactor is about 45 tons of spent fuel and 9 tons of cladding. Reprocessing would result in only 5 tons of solidified waste plus about 30 tons of reusable U and 600 lbs of Pu (Dukert, 1975, p. 10-11).

This means that at least one and perhaps three of these "average" repositories of 35,500 canisters in salt rock or two and perhaps five in crystalline rocks, will be required by the year 2000, and that after 2000, one new repository will have to be opened every 5-20 years in salt rock or every 3-11 years in crystalline rock just to accommodate a steady-state nuclear capacity of that projected for the year 2000--about 380 GWe. If nuclear demands should exceed 380 GWe per year, the establishing of new repositories would have to be at even faster rates (IRG Report, 1978, p. 8).

The essence of all the above assumptions and generalizations--and allowing for wide margins of uncertainty and error in projections--is that, before long, many repositories will be required. Based on the experience of identifying potentially suitable sites in salt rock and shale, a logical conclusion is that repositories will have to be sited in a variety of rock types. For this reason alone, repositories may well have to be sited in a number of geographic areas, as recommended (for nongeologic reasons) by the IRG Report (1978).

REQUIREMENTS FOR ISOLATION

Inasmuch as the most probable medium for transporting the waste to the biosphere is water, the prime criterion for isolation becomes a hydrologic one. Specifically, the net effect of (1) the rate of entry of ground water into the repository site, (2) the rate of corrosion of the canister, (3) the rate of dissolution of its contained radionuclides by the ground water, and (4) the rate of flow of those nuclides in the ground water must be sufficiently slow and the flow path sufficiently long so that those nuclides will not reach the biosphere until they have diminished to safe levels.[5]

This prime criterion is the same regardless of the specific host rock. However, fundamental differences in the physical and chemical conditions and properties of various rock types and the regional terrane in which they occur affect the above rates in different ways. For example, hydrologic characteristics are highly dependent on permeability. In crystalline rocks, whose matrix permeability is extremely low, bulk permeability at the surface, and to some depth that needs to be determined, is dominantly fracture permeability. Hence, hydrologic characteristics are highly dependent on depth and on degree and type of fracturing. These in turn are functions of the tectonic and seismic history and resultant present state of stress, and the rates and changes in rates of strain in the rock. These all are factors which affect, are affected by, and partly are deciphered by: (1) the nature of microfractures and pores, (2) the mineral phases presently in the rock, (3) the mineral phases that will form during the thermally and chemically active life of the waste emplaced within the rock, and (4) the equilibrium state of some natural-isotope systems. Thus, there is a complex and interdependent play of major processes and conditions. All must be thoroughly understood in order to be able to know how fluids presently move through the rocks, and the likely ways in which that movement will change with time. Reasons for possible changes in that movement are perturbations caused by the excavation itself; the presence of added heat and radioactivity; the possibility of reactions of host rock and chemical waste; and the effects of changes in climate, volcanism, heat flow, seismicity, and tectonic activity. It is important to note that these conditions and processes are about equally incompletely known for all host-rock types--salt, shale, granite, etc.

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[5]Diminution is by one or more of: dilution, radioactive decay, sorption (the combined effect of absorption and adsorption), ion exchange, and fixation by chemical reactions. "Safe levels" refers to concentrations which presently are thought to be harmless and acceptable in drinking water or other substances ingested by humans.

In order for a site--in any rock medium--to be suitable for waste isolation, the net result of all the factors and processes presently in effect and those predicted to come into effect in the region during the hazardous life of the waste must be that of achieving the prime criterion of long-term hydrologic isolation.

Some criteria, in the sense of attributes, would be more important in the absence of some others. Many combinations of processes work synergistically--not only is their "whole" greater than the sum of their parts, but some effects (good or bad) may be achieved for which each process acting alone would be incapable of achieving to any extent. It is an acknowledgment of this complex interdependent nature of the problem that led the NRC (1977, p. 6) to propose that ". . . although it may be impossible to find a site where each feature of interest is at an optimum state, e.g., optimum geologic conditions and optimum hydrologic conditions, this may not be necessary. Instead, a balance can be struck between the geologic, hydrologic, and engineered features of the repository system as a whole so that the entire repository system will ensure protection of man and his environment, i.e., overall system performance is [of] prime importance." The IRG Report adopted this same term--system performance--and used it in the same sense as did the NRC. It is "the net result . . ." described in the preceding paragraph.

The overall relations of elements within the entire "repository system" are shown on figure 1 and in table 2. These also illustrate the steps required in the exploration for regions, and then sites, and for subsequent verification of sites.

The wide variety of tests required to answer each of the "yes" "no" decisions of figure 1 require an equally wide variety of geologic skills. The skills, and the state-of-the-art in achieving them, are elaborated in detail by the LBL (1979) report. Not all those data and the means of acquiring them are well known or well developed.

The required net slow rate of flow (fig. 1) must be achieved by selecting appropriate host-rock media in favorable hydrogeologic environments. This includes some combination of:

a. Sufficient depth below zone of ground water.

b. Low hydraulic gradient.

c. Suitable homogeneous rock of large volume and very low permeability.

d. Rock with good sorptive properties.

e. Structurally stable terrane environments.

Additional assurance of safety can be provided by back-up systems of manmade barriers which include:

f. Canister constructed of materials highly resistant to corrosion by water of the composition to be encountered at the site.

g. A waste form designed to be highly insoluble in the natural hydrologic environment of the specific site.

h. Packing the canister and filling the tunnels with material that forms a very tight hydraulic seal.

i. Packing the canister and filling the tunnels with material which is highly sorptive of the specific radionuclides in the waste, and the chemical complexes which they may form once dissolved.

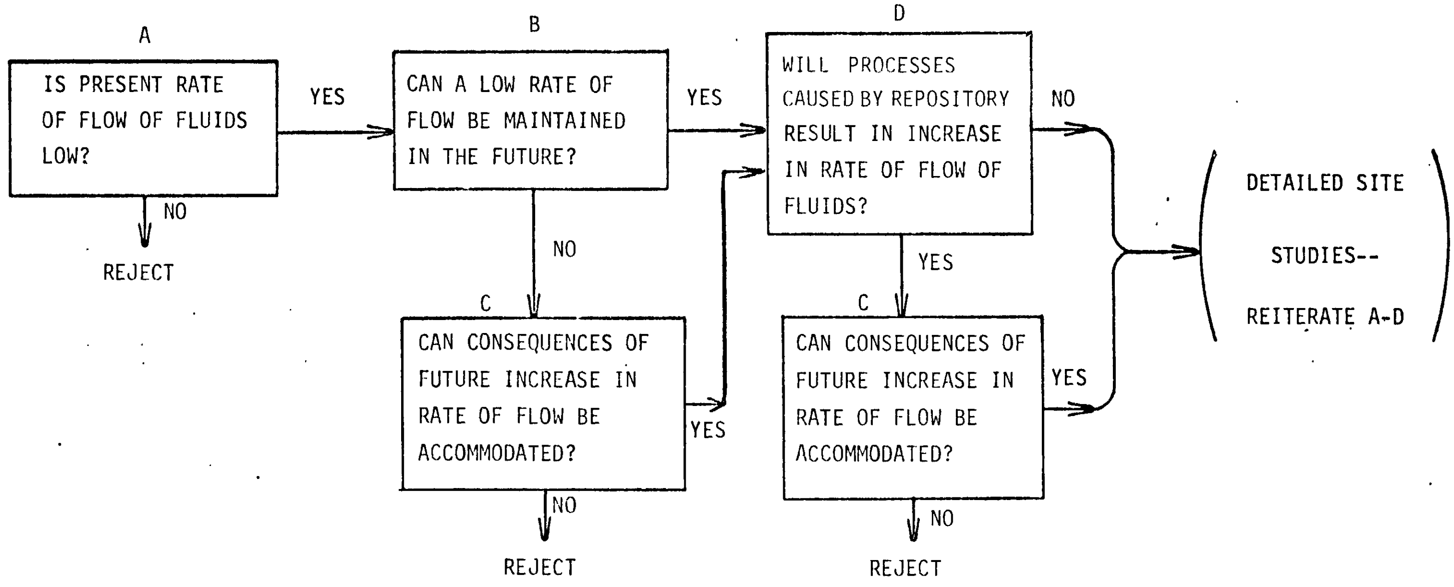

Figure 1.--Analytical flow of decisions for verification of repository site.
[For examples of processes and conditions to be evaluated for each stage, see table 2, p.13]

Table 2.--*Examples of factors (processes and conditions) to be evaluated for decision at each stage shown on figure 1*

Decision stage	Factors
A	1. Distribution and character of rock types, their depths, structures, and structural and age relations.
	2. Permeability, including:
	a. Intrinsic (or primary) permeability, its change with pressure (depth), and its relation to mineral orientation in the rock (fabric).
	b. Fracture permeability and its change with pressure (depth). This should be too low to measure directly in a reasonably short time, so will need to be calculated knowing such things as the character, spacing, and connectivity of faults, joints, and microfractures, and the change in their behavior with pressure (depth). Fundamental research will be needed to develop ways of relating all these attributes.
	3. Hydraulic gradient.
	4. Recharge area and rate of recharge.
	5. Discharge area and rate of discharge.
	6. Distance to nearest discharge point.
	7. Travel time of nuclides in ground water, from repository to discharge point (from 2 thru 6, above, and data on sorptive properties along path).
B	1. Seismic stability (will need to develop criteria for establishing acceptable limits and for assessing probability of future change, and nature of change, of seismicity, and the consequences).
	2. Tectonic stability (will need to develop techniques of establishing past history of tectonic events, partly through geomorphic analysis, and by applying isotope and microfracture data as described below).
	3. Geothermal stability (study trends of compositional changes, patterns, and periodicity of volcanism and plutonic events; and determine current heat flow, including relation to heat production of the rocks).
	4. Hydraulic stability (develop ways to assess past climatic/hydrologic history, and probability and consequences of future changes). Includes evaluation of consequences of possible manmade changes in flow rate by such things as future new or additional need for water. That may result in drilling of wells or pumping down from existing wells and changing the hydraulic gradient.
	5. Stress stability
	a. Change in behavior caused by decompression related to erosional unloading.
	b. Unloading due to excavation of chamber.
	c. Thermal stress.
	d. Relation to tectonic and thermal stability.
	6. Capability of modeling all the factors.
C	1. Sorptive properties of host rock.
	2. Hydraulic pathway.
	3. Sorptive properties along pathway
	4. Properties, performance, and behavior of engineered barriers.
	5. Composition and possible reactions among water, canister, and waste.
D	1. Rock strength.
	2. In situ stress, effective stress, and residual stress.
	3. Stress due to excavation.
	4. Thermal stress.
	5. Chemical reactions (effect on rock strength, sorptive properties, permeability, stresses due to gas evolved; chemical gradients; and upward buoyant movement).

Criteria

Criteria for waste isolation have been described in numerous reports published over a span of more than 3 decades. At the top of virtually every list of criteria are those that say the area must be: (1) dry, (2) tectonically stable, (3) of low seismicity, and (4) away from faults. The difficulty comes in verifying that these conditions can be met. These criteria generally have been elaborated on in terms of conditions or attributes such as thickness, depth, and strength; or processes such as subsidence, faulting, and chemical reactions. Each of them is stated in terms that indicate that the present or future activity of the attribute or process:

Will not compromise[6] the site

Will preclude breaching of the repository

Will not compromise isolation

Will protect the waste against surface processes

Will not pose a threat to the integrity of the site (reference to NRC, National Research Council, EPA, DOE, ERDA)

Some criteria serve for culling or screening in the exploration to select, first, candidate regions and then, sites.[7] Some of these same criteria, but of a far more detailed and precise nature, as well as other criteria, subsequently serve for verifying the suitability of the selected candidate sites. In recent years there have been numerous reports dealing with the requirement for, and methods of, testing to verify that a specific site does indeed meet those criteria. The most comprehensive of these is the symposium proceedings by LBL (1979).

The criteria cited apply universally, regardless of the host-rock medium. Therefore, it is a principal point of the present report to evaluate how well terranes of crystalline rocks are apt to measure up to these criteria in comparison with salt, shale, and other rock masses.

Criteria have been listed using many different categories of classification[7] especially those that inlcude strength, stability, and integrity. Because these three, especially, are so complexly interrelated and overlapping, I have chosen to adopt the system used in the recent summary report on criteria published by the National Research Council (1978)[8] as follows:

1. Geometry
2. Stability
3. Hydrology
4. Geochemistry
5. Geoeconomics

One of the most formidable tasks faced in the exploration of any rock medium is that of determining values of its relevant attributes throughout a large mass in sufficient detail to be able to characterize that mass and to be able to know when we have adequately[9] characterized it. All this is required in order to be able to model the total system, for assurance of

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[6]This jargon has crept into the literature of waste management, and is very widely used. The term "compromise" may have come from the vocabulary of intelligence agencies and the military. It has the sense of "to endanger" or "to be laid open to danger." The term "integrity" probably came from the jargon of aerospace technology. Its sense is "the condition of being unimpaired," in this case, in terms of its capability to isolate the waste. The two terms relate in the following way: if the integrity of the site has been damaged, the containment has been compromised, and the site cannot be relied on.

[7]In this report, I am considering only the major geologic criteria, whereas many of the published criteria also include socioeconomic and demographic criteria.

[8]In the following pages, criteria are paraphrased principally from the National Research Council report (1978), and elaborated upon.

[9]A question raised later in this report (in the section on prediction) is this matter of adequate versus complete characterization--and of knowing when characterization is adequate. Adequate characterization of a potential site may require in situ tests at depth.

long-term isolation. It is widely held that these values must be determined largely by means other than drilling, for the presence of drill holes would itself modify the performance of the total terrane system, and would imperil the safety of isolation--therefore, drilling must be kept at a minimum, and geophysical techniques be used instead. This premise also needs to be tested, for there probably is some reasonable tradeoff between excessive penetration and total reliance on indirect geophysical methods.

For several reasons, it seems prudent to allow for the possibility of ready retrievability of the waste for decades. Policies can change, but the repository--once built--cannot be easily changed. Plutonium, unfissioned uranium,[10] and other important elements in the spent fuel may well become an important resource in the future. Regardless of how well the site is explored and how conclusively it is verified, unforeseen events (NRC, 1978, p. 9; Bredehoeft and others, 1978, p. 10-12) causing a safety problem in the near future may necessitate exhuming the waste and moving it to another site.

If geologic conditions and constraints indicate that a repository can provide isolation only at a depth somewhat greater than presently planned (500-1,000 m), the system should allow feedback of those data for consideration in effecting a change in the designed depth.

The geologic record indicates that nature can initiate changes which must be taken into account. Examples are changes in ground water brought on by changes in climate, changes in surface water brought on by stream capture, and changes in physical stability and integrity of the rock mass brought about by changes in seismicity or tectonism. Full consideration of criteria for site suitability must also take into account possible changes in these geologic conditions (fig. 1; table 2). Therein lies the greatest uncertainty.

Criteria in the five categories listed above are complexly interrelated, as criteria related to any total natural system must be, and because they all must relate to the one basic criterion of total radionuclide isolation. Because such attributes as permeability, hydraulic conductivity, state of stress, rock fabric, composition, and structure will differ from one site to another, the net effect of their complex interplay will differ. Therefore, a general criterion of what constitutes "large enough" (geometry), "stable enough" (stability, geochemistry), and "long enough hydraulic flow path" (hydrology), for example, should not be stated any more quantitatively than that. To get this notion accepted by the general public is another of our formidable tasks, for this concept will cause frustration and misunderstanding among those who find comfort in unqualified "one-liners" and in absolute numbers.

Although all the following may have the appearance of a shopping list of geologic skills, it is intended as a portrayal--a sample, at that--of the complexity of the problem, the interplay among many conditions and processes, and by implication, the magnitude of the research effort required to solve the problem. Note, especially, that virtually all of the conditions and processes mentioned--all of the complexity--apply regardless of the rock medium being considered. It seems incontestable that, without long-term geologic stability, waste isolation becomes more difficult to assure. With the possibility of actual rupture of the canisters or, at the least, increased access by ground water to and away from the site, it is difficult to predict or model the behavior of the total system over the long term.

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[10]Dukert (1975, p. 10-11) indicates that spent fuel contains approximately 67 percent uranium and 0.7 percent plutonium.

Geometry

The host-rock mass must be "large enough" to encompass the repository and an undisturbed peripheral zone large enough to provide a buffer between the host rock and adjacent rock masses. The host rock must also be large enough and impermeable enough so that there is a long and slow hydraulic flow path through it and other rocks encountered by the ground water before it reaches the biosphere. This criterion typifies the complex interrelationships among all the criteria, for "large enough"--and all of the other "enoughs"--can only be determined by knowledge, in each region, of: (1) relevant properties and behavior of the rock masses; (2) mutual structural relations of rock masses; (3) the state of stress; (4) hydrology; (5) the hydrologic properties of any overlying younger sedimentary and volcanic rocks and unconsolidated deposits; and (6) the three-dimensional distribution of all the rock phases (inhomogeneities), and their properties throughout all possible flow paths. "Large enough" also means thick enough to contain the shaft, tunnels, chambers, and other underground workings, and to provide the strength necessary to prevent subsidence and other surface processes such as erosion, fire, flooding, or meteor impact from reaching or breaching the waste, or in other ways compromising its safe containment. All of these, and other data, are as well known--or unknown--for crystalline rocks as for any other.

Stability

Because the prime criterion (hydrologic) of isolation requires that the host-rock mass in the repository region presently have low permeability, it is essential that this be maintained in the future. Causes of potential adverse changes in permeability are related to changes in the stability of the site and region. Stability factors include: (1) the strength of the rock; (2) natural forces and processes unrelated to the presence of the repository and the waste, such as tectonism, volcanism, seismicity, and erosion; and (3) forces and processes related to the presence of the repository and waste, such as near-term effects on the mechanical and chemical behavior of the rock due to heat from and chemical reactions with the waste, and long-term mechanical behavior of rock during and after the long period of cooling of the waste.

Repositories should be in rocks that are strong enough to minimize the cost and to ensure stability of the underground excavations, at least during the active life of the repository (until backfilled and sealed). "Strong enough" involves more than just a laboratory measurement of rock strength. Strength must be considered in context with other properties, such as in situ stress--violent rockbursts usually occur in very strong rock. These in situ stresses, and heat-induced strain, must be accommodated by the rock properties, mining techniques, and waste form. Widespread rock failure would result in increased permeability and, conceivably, rupturing of canisters.

We must determine, from the geologic record, that the rock mass will not be subject to adverse increases in seismicity or tectonism. Laboratory and in situ testing supplemented by computer modeling will help determine the limit of magnitude beyond which constitutes an "adverse increase." An increase in either seismicity or tectonism might cause the rock mass to be fractured and weakened, prevent retrievability, permit surface or ground water to enter the repository and dissolve and transport the waste faster than is acceptable because of increased permeability. In the extreme case of failure, the waste canisters themselves might be ruptured.

The possibility of future increase in heat flow or volcanism must be evaluated and, if deemed probable, the site rejected, for this increase would not only adversely affect the permeability and hydrology, but would weaken the host rock and, in the case of volcanism, might cause total destruction of the repository site. Additional effects would include that of raising the temperature at the site long after the waste had cooled. This would stimulate the rates of later chemical reactions that could be harmful.

Tectonism.--For more than 30 years, one of the top three criteria universally proclaimed for geologic disposal of HLW waste is that the area must be tectonically stable. Who could disagree? But how is this condition defined and determined? It may only be a matter of semantics, but one must first ask what constitutes tectonic stability, for it could mean maintaining a steady state (equilibrium) of deformation. The sense intended, of course, is to be static. Most likely there is no place on Earth that is completely stable tectonically. The task is to select areas that are the least tectonically active, and not be concerned about whether that is absolutely zero, or only relatively so.

The most readily available and most easily understandable measure of tectonism is that of vertical and horizontal movements. Plate movements are largely horizontal, though they give rise to vertical movements, and are of higher rates but are less well known. The literature on vertical movements is voluminous but, until recently, no nationwide compilation existed. A map by Holdahl and Morrison (1974) presented a highly schematic portrayal of probable vertical movements of the Earth's surface. However, this was based on relevelling surveys and tide-chart data, covering only the last 100 years or less of tectonic activity. Because that map was too generalized and did not cover a sufficient period of time for predicting very long-term future stability, Gable and Hatton (1980) prepared a far more detailed set of maps. One covers the period extending 10-12 m.y. before present (see fig. 2 this report); another extends back only to the end of the glacial period and includes an update of the historic data referred to above. These maps show amounts and rates of vertical movements which, with amplitudes of folds (not shown), serve as the best, and presently, the only readily accessible quantitative guide to degrees of tectonic stability as judged by vertical movements. Lateral movements (such as along the San Andreas Fault system) are important but have not yet been dealt with, except as noted in a following section on faulting. These maps of vertical movements constitute a highly valuable "progress report." However, they are of small scale and based on incomplete and, in places, conflicting data.

It has long been known that the Earth's crust is broken by major faults into a complex of large blocks that are structurally intact. Early examples are in reports by Hobbs, 1911; and Sederholm, 1913. Other examples are shown by Sonder, 1938; Vening Meinesz, 1947; and Thomas, 1974. Examples discussed in relation to waste repositories are reported by Gale and others, 1976. With these structural blocks in mind, and the incomplete nature of the map data for vertical movements, the following may occur: (1) suitably stable blocks of sufficient size to be a host for repositories exist within large areas that are indicated as having high magnitudes of vertical movements and (2) although large areas may be tectonically stable, they are composed of several structural blocks whose boundaries could strongly influence the hydrology even though little or no relative vertical motion has occurred across them in the past 10 m.y. or more. The importance of determining the locations of these blocks is to consider only sites centrally located within the block or located closer to one boundary than another depending upon the hydraulic vectors in the boundary zones.

Faults and Faulting.--Perhaps the very first criterion ever stated for sites is that they must be away from any faults. This is because every fault could be considered potentially active over very long periods of time, making the area tectonically unstable.

The NRC criteria (U.S. Government, 1978, p. 7) state that repositories should never be placed in areas of inactive faults if movement across those faults has occurred within the last 1 m.y. This limit seems far too short, for a rapidly accumulating mass of evidence indicates that movement has recurred episodically across faults which originated during Precambrian time (more than 600 m.y. ago). Even though there might not have been movement in the last 1 m.y., they should be avoided, because the periods of quiescence of some of these faults is on the order of a few million to a few tens of millions of years. As an example, one such fault zone in southwestern Montana had major displacement at least as far back as about 78 m.y. ago. The next three periods of movement across this zone came at about 8- to 10-m.y. intervals (Smedes, 1973). Other faults in that region represent early Precambrian intraplate boundaries (Reynolds and Kleinkopf, 1977; Smedes, 1958). Since Precambrian time, there has been episodic movement, and the zone is the site of present-day earthquake hypocenters. These zones of recurrent faulting mark boundaries of some of the structural blocks or domains mentioned above. This supports the advisability of avoiding numbers in the criteria--they can only be specified for a given site, based on the effect of all processes and conditions acting in concert.

The importance of this criterion is undeniable. However, there is implied in the stating of it--"stay away from faults"--that we know the location of all the faults. Nothing is farther from the truth! Because of this, in moving away from a known fault, one may well be moving dangerously close to an unknown and perhaps more detrimental one. Even if we did know the location of every fault, the question arises: "How far is far enough away?" One answer is to (somehow) characterize each fault--its periodicity, the average and the range of displacement, and so on. This is not at all feasible. Perhaps a more realistic and attainable answer, which I propose, is that the clues may be contained in the rocks themselves, as follows: It seems to me that a fault would have an associated quasi-symmetrical gradient of stress normal to it. That is, away from the fault in both directions there should be a decrease in macroscopic and microscopic strain features[11] such as spatial density of: joints (whose trend may not be that of the regional joints), cataclasis, strain shadows in quartz, deformation lamellae, and the nature and abundance of microscopic and submicroscopic fractures. At some distance, these features should diminish to some level which is characteristic of the region (a background level), and some may disappear. The degree of asymmetry quite possibly would indicate the direction of dip of the fault, including low-angle thrust plates. Any distance beyond the disappearance of those strain effects could be considered as "far enough" away from that fault, as far as this one criterion is concerned.[12] If such a relationship can be demonstrated for known faults, it provides the potential of an effective means of detecting previously unknown faults.

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[11]Support is given to this concept by the studies of Lee and others (1979) and Sbar, Engelder, and Tullis (1978, p. 485-502), which suggest that in situ stress patterns change as major fault zones are approached, and by the stuuies of the USGS at Rainier Mesa (NTS) which show perturbations of the stress field near minor faults (W. L. Ellis, written commun., 1979).

[12]Modeling of hydrologic transport may indicate the distance is still not "far enough" but for various reasons other than tectonic stability.

Seismicity.--Although there is some aseismic faulting, faulting most commonly gives rise to earthquakes. Until recently, the probable magnitude of seismic vibration was a criterion of high rank. This is understandable because of the common association, in our minds, of earthquakes, faults, and great mechanical destruction. A few years ago, it was thought that the Seismic Risk Map (Environmental Science Service Administration, 1951) and the subsequent horizontal motion map (Algermissen and Perkins, 1976) would serve as the first and best means of culling large areas as clearly being unsuitable as candidates for repositories--in any rock medium.

The latest of these maps (Algermissen and Perkins, 1976) is based on a probabilistic approach to assess the maximum horizontal motion of the ground during the next 50 years. As those data are recalculated for successively longer periods of time, the areas of each specific increment of ground motion will become successively more extensive than on the 50-year map. These studies currently are underway. The reasoning for this approach includes the consideration of "capable" faults and the well-known linear relation between intensities of an earthquake and its recurrence interval. If we still thought that these ground-motion data would be a prime criterion for culling, the result would be rejection of successively larger areas--perhaps all areas.

On second thought, one could consider that certain rocks may have physical properties such that they can experience high seismic vibration without any cracking or other effects. In that case, they would have been "tested" repeatedly, and passed the test! Why should they be rejected? This is to say that the clues probably lie in the rocks themselves and in their constituent minerals.

Important recent data (Dowding, 1978; Yamahara and others, 1978; U.S. Department of Energy, 1979) have shown that seismic motion is rapidly attenuated downward. The result is that in an area where surface structures are damaged by an earthquake, the vibration is weak (one-third or one-quarter the surface intensity) or largely imperceptable by people in underground structures such as mines. According to Bartlett and Koplik (1979, v. 7, p. 2.2):

> "The following factors appear to be adequately understood at present: Earthquake Protection: Most portions of the repository [in salt] will not experience structural damage from all [sic] but the closest earthquake if normal design procedures are followed. These include all parts of the repository not located in soft or unconsolidated sediments that may be found near the surface."

The conclusion is that the magnitude and frequency of ground motion (seismic vibration) need be of concern only (or primarily) in providing a base for establishing design parameters for (1) the structures at and near the surface which are to be used for handling the waste during the phase of loading the repository; (2) rock belts and other methods of preventing damage to the free surfaces underground; and (3) possibly for appropriate backfill material to match the vibration period of the host rock.

Folds and Folding.--Folds can be produced by processes such as vertical uplift, intrusion by magma to form laccoliths, etc. (a special kind of vertical uplift); large-scale slumping; and regional compression during mountain-building (orogeny). They are a partial record of a region's tectonic history and its degree of tectonic stability. Although many terranes

Table 3.--*Approximate mineral composition (Larsen, 1942) and average chemical composition (Daly, 1942) of major granitoid igneous rocks*

	Granite	Syenite	Grano-diorite	Quartz Diorite	Diorite	Gabbro
Quartz	25	..	21	20	2	..
Orthoclase and Microperthite	40	72	15	6	3	..
Oligoclase	26	12	..	..	..	..
Andesine	..	..	46	56	64	..
Labradorite	..	..	..	..	..	65
Biotite	5	2	3	4	5	1
Amphibole	1	7	13	8	12	3
Orthopyroxene	..	..	..	1	3	6
Clinopyroxene	..	4	..	3	8	14
Olivine	..	..	..	..	..	7
Magnetite	2	2	1	2	2	2
Ilmenite	1	1	..	..	..	2
Apatite	tr	tr	tr	tr	tr	
Sphene	tr	tr	1	tr	tr	..

	Gran-ite	Sye-nite	Gran-odi-orite	Quartz Di-orite	Di-orite	Gab-bro
SiO_2	70.18	60.19	65.01	61.59	56.77	48.24
TiO_2	0.39	0.67	0.57	0.66	0.84	0.97
Al_2O_3	14.47	16.28	15.94	16.21	16.67	17.88
Fe_2O_3	1.57	2.74	1.74	2.54	3.16	3.16
FeO	1.78	3.28	2.65	3.77	4.40	5.95
MnO	0.12	0.14	0.07	0.10	0.13	0.13
MgO	0.88	2.49	1.91	2.80	4.17	7.51
CaO	1.99	4.30	4.42	5.38	6.74	10.99
Na_2O	3.48	3.98	3.70	3.37	3.39	2.55
K_2O	4.11	4.49	2.75	2.10	2.12	0.99
H_2O	0.84	1.16	1.04	1.22	1.36	1.45
P_2O_5	0.19	0.28	0.20	0.26	0.25	0.28

resulted from repeated episodes of folding, some have been affected by only one, if any. The likelihood of recurrence of these kinds of deformation can be evaluated on the basis of such things as the regional structural history, and the present position and past history of presumed subducting plates in the crust.

The compressional forces that were in operation produced strain that may have been relieved by the formation of sets of compressional, tensional, and shear fractures, and of overthrust plates. If the stresses were sufficient, as in overturned folds and folds resulting from vertical movements, dislocation along the fracture would ensue. These are faults. Whether these fractures have developed or are latent, and whether they are open or filled with (cemented by) low-grade minerals, will highly influence the strength of the rock as well as its permeability.

Hydrology

In addition to the broadly stated requirement of hydrologic isolation, there are some specific hydrologic criteria or attributes that must be determined. Basically, the combined effect of low rate of flow, long flow path, and the effects of sorption must result in long-term isolation. This is easy to state--a truism, really--but is very difficult to determine.

Each of the above three factors is a complex function of such varied things as composition of water, rock type, structure, topography, and climate. Some of these have already been discussed in earlier sections of this report. An excellent summary of the scope of the problem is presented in the LBL (1979) report. Active research on hydrology related to radionuclides has been underway by the USGS and other Federal and State agencies and research laboratories for several decades.

The rock type and structure affect the rate of flow by determining the permeability; they also affect the sorption by the composition (rock type) and the access of water to the sorptive minerals in the rock (permeability and structure). Topography influences the configuration of the ground-water surface and the gradient . . . areas of low relief are preferred, therefore; climate affects the gradient, hence rate, by rate of recharge. Because of the dependence of flow rate/path on these attributes, it is essential to be able to evaluate the consequences of changes in any one or combination of them on the overall flow rate and path length.

When water eventually does reach the waste, as it undoubtedly will, its behavior of concern then will fundamentally be that of the nature of its reactions with the canister and then the waste. The aspect of chemical reactions is briefly described in the following section. The subsequent hydrologic conduction of the dissolved nuclides must be in accordance with the above-stated requirements of slow and long path. It is at this stage that sorption becomes an important factor.

Inasmuch as the ground water is a potential resource, consideration must be given to the effects future ground-water development would have on the rate of recharge, hydraulic gradient, and other hydraulic characteristics. Effects of changes in the surface and subsurface hydrology by constructing dams and reservoirs must also be evaluated.

One of the more important hydrologic factors is one about which we know the least. That is, how effective a hydraulic seal can be made to plug the shaft of the repository and the holes used for inserting monitoring instruments. Once surveillance of the repository ceases, the shaft and the holes used for monitoring (if other than the shaft), of course, provide a potential "short cut" from the waste to the biosphere. If water were to enter by way of the shaft, the heat from the waste would provide circulation that could bring the radionuclides into the surface or ground water.

As far as I can determine, no modes of plugging have been tried or proposed for which there is some natural example. Without some natural example to provide clues to truly long-term effectiveness--to give us geologic-time "leverage" for predicting--this will remain a severe problem of uncertainty. As many natural and engineered barriers as possible will be needed to provide assurance that surface and ground water will not be able to enter the repository by this route.

There has been widespread concern with the problem of fracture hydrology, especially in crystalline rocks. This major problem is discussed in a following section.

Continental glaciers have covered much of the northern U.S. (fig. 8), and alpine glaciers have occupied the higher parts of mountainous areas in the western U.S. Although the Precambrian shield terrane in the Great Lakes region has undergone numerous glaciations, the glaciers have caused only superficial erosion and fracturing. Isostatic subsidence and subsequent rebound uplift of the crust in areas of continental glaciation is a slow process covering a large area. The present maximum rate is 2 or 3 mm per year; the amount of tilt (gradient of the present rebound uplift) is less than 1 mm per 100 km (from maps of Gable and Hatton, 1980). That is less than 1 in 100 million! No wonder the crust is not broken.

The locations of present and future probable alpine glaciers are known. They are in areas of high relief that probably should be avoided for repositories for that reason alone.

Re-advance of continental glaciers will proceed very slowly. There will be ample time to explore, verify, construct, fill, and then close and seal a repository, and monitor it for decades before an ice sheet would reach the area. It thus appears that continental glaciation poses no threat to a repository.

At the other climatic extreme, long-term climatic warming would result in melting of glaciers and polar ice caps. The extreme would produce a rise of sea level of about 200 feet (Flint, 1971). This would result in the inundation of coastal areas, as shown on figure 8, affecting only limited areas of crystalline rocks (compare with fig. 5). If the shaft and drill holes are properly sealed, there is no reason to expect that the ocean water would automatically percolate down to the repository level. There are many areas where mines and tunnels have extended beneath deeper bodies of water than would exist by this flooding, and these did not become invaded by the water. Most of the areas that would be inundated are underlain by major aquifers (U.S. Geological Survey, National Atlas, 1970, p. 122-123). If it can be determined that these aquifers would not leak into an underlying repository, then the inundating shallow sea certainly would not.

Geochemistry

In previous discussions of geochemical criteria, such as NRC (U.S. Government, 1978, p. 11-13), a few specific relations or reactions that might jeopardize the containment were listed. For example, water reacting with rock, and water reacting with the waste, have been split out and discussed <u>separately</u>. Because of the complex interplay of the total physical-chemical system with time, the criteria are presented in the following way:

Geochemical criteria fundamentally require that the site not be compromised at any time during the hazardous life of the waste by any effects resulting from the behavior of one or more or reactions among any combination of the following factors:

1. Radioactivity of the waste. Although these effects will be limited to the region very close to the canister they may result in the liberation of gases or in the breakdown of minerals, making them more susceptible to further alteration.

2. Heat produced by radioactivity of the waste. This criterion refers to ways in which heat affects the composition of the host rock and enhances chemical reactions. (Strictly physical effects of thermal stress are discussed above.) This heat will decrease rapidly during the first few hundred years while fission products decay, and will decrease relatively slowly thereafter while decay of the long-lived radionuclides predominates. One year after removal from a reactor, one spent-fuel assembly will have thermal output of about 4.8 KW. As noted above, the spent fuel will be 10 years old by the time it is sent to the repository. By that time, the thermal output will have been reduced to about 0.55 KW. By 50 years, the thermal output will have diminished to 0.25 KW; by 100 years, 0.13 KW; 500 years, 0.045; 1,000 years, 0.026 KW and 10,000 years, 0.006 KW (Kisner and others, 1978, p. 41-42). The thermal output for a canister of solidified reprocessed waste is higher for the first few hundred years; 1 year, 22 KW; 10 years, 3.1 KW; 100 years, 0.36 KW; 1,000 years, 0.2 KW; and 10,000 years, 0.006 KW (Mendel and others, 1980, p. 20).

In underground tests of the thermophysical behavior of granitic rock (quartz monzonite and granodiorite) at the Climax stock of the Nevada Test Site, it was noted that about one-third of the heat generated was exhausted by the ventilation system.

3. Composition of the host rock, including preexisting sorptive and microfracture properties; and the composition and amount of pore water originally in the rock.

4. Composition and distribution of sorptive minerals and nature of microfractures that may develop in the presence of heat from the waste.

5. Composition and physical properties of the canister and its sealant/packing material. These are to be designed to be of low solubility and permeability, so as to retard flow of water and delay the time at which corrosion and dissolution will begin.

6. Composition of the waste form. Although the waste form (ceramic, glass, etc.) is to be designed to have low solubility, we must assume that water will reach and dissolve the waste form eventually. Ground water at 100°C will corrode all ceramic waste forms to some extent within 1 month (Fyfe, 1977, oral presentation of paper cited). Therefore, it is especially important to keep ground water away from the waste by some kind of barrier during the thermal life of the waste (ca 100 yrs). Clearly, the longer that ground water can be prevented from reaching the waste, the less will be the chances of jeopardizing isolation of that waste.

7. Composition of ground water that must be assumed to reach the waste eventually. That water may well have a composition different than the water presently in the rock at the site.

The behavior of these factors (1 through 7), the likelihood and rate of interactions among them, and the magnitudes and spatial extent of the effects of the interactions all will be functions of time and temperature. Although radioactivity will persist at some level, the breakdown of minerals that it may cause could be effective at the onset by making these alteration products available at a time when heat is still emanating from the canisters into the rock, as well as at any time thereafter.

If, as planned, water will be delayed for many centuries or millennia from reaching the waste, heat from radioactive decay would have greatly diminished and would not be considered as a factor in chemical reactions at that time. However, the heat will have had its role to whatever extent the rocks contained some pore water, for this water will have reacted with the rock on a microscopic scale; and by thermal stresses having increased the microfractures to provide greater surface area for these and subsequent (low temperature) reactions to take place. Ways in which these effects can prove to be beneficial for waste containment are described later.

Multiple natural and manmade barriers provide a backup system that can help compensate for possible unforeseen processes or conditions, and to provide a further level of assurance. Each rock type has its own good and bad attributes, and natural barriers, but the engineered barriers are largely independent of rock type. They are discussed briefly in the order in which ground water would encounter them, they are: (1) the material used to backfill the shaft and chambers, (2) the material used as a packing and sealant around the canister, (3) the canisters themselves, and (4) the waste form.

Research for each of these stages is being actively undertaken at present. For the backfill material, it may be desirable to use the excavated rock. This would eliminate reactions between bedrock and fill and would provide strength to prevent significant collapse or subsidence of the roof. However, unless mixed with some special material whose properties provide a good hydraulic seal or high sorption, little has been gained as a barrier. Probably for this reason, the Canadian program plans (oral presentation by AECL, Niagara, Ontario, April 26, 1979) for spent fuel involve fuel rods encased in lead, with a backfill (in granite) of bentonite, sand, and crushed granite (possibly with some other material possessing high sorptive properties); the reprocessed waste would be incorporated in borosilicate glass, placed in canisters in holes packed with compressed bentonite.

A popular material for the packing around the canisters is a highly compressed mixture of sand and bentonite (Roland Pusch, oral commun., Univ. Luleå, Sweden, 1979). This material is suitable only if the skin temperature of the canisters is less than 100°C, because at about that temperature bentonite would break down to form illite and water (steam). And, of course, it is essential that water be kept away from the waste--especially hot water and steam! This method seems well suited for the waste in Sweden whose skin temperature is designed to be only 65°C.

A commonly held belief in this country is that the canister will not survive long and therefore does not constitute a significant barrier (Cohen, 1977). This view may well be valid for the type of canister which the DOE presently is considering--stainless steel and carbon steel. Ringwood (1978, p. 7) stated that, because of its high chromium content, stainless steel will be thermodynamically unstable in a natural geological environment, and that it will surely disintegrate in a short time. Copper has been recommended by Fyfe (1977) and others because of its demonstrated long-term (>10^8 yrs) geologic stability, and copper will be used in the Swedish program. Ringwood (1978) proposed using the alloy Ni_3Fe, which is known to have been stable in certain geochemical environments for more than 100 m.y. If such canisters are incased in fill of crushed serpentinite and magnesium oxide, they will be extremely stable. Water would cause the MgO to hydrate, forming brucite ($Mg(OH)_2$) with a resulting twofold increase in volume. This would form a highly effective hydraulic seal. The chemical environment of serpentinite and brucite would buffer the system and maintain the Ni_3Fe of the canister in its field of thermodynamic stability. In addition, the expanded mass of backfill would add support to prevent subsidence or collapse of the roof, provided, of course, that appropriate volumes of backfill were used so that the twofold expansion would not overly stress the host rock and cause fractures to develop.

An innovative and thought-provoking concept of Ringwood (1978) takes advantage of the known superior chemical stability of many crystalline rocks by proposing that the waste be a component of a synthetic rock (SYNROCK) produced in the laboratory by cooling of a melt of the waste and the components of the silicate rock. This seems to be an extension of the ceramic concept, which also implies an acknowledgment of the superior properties of silicate and other high-temperature anhydrous minerals. Ringwood's concept is not unlike that of an earlier proposal to emplace concentrated waste in very deep drill holes where the heat generated would cause the surrounding rock to melt. Subsequent natural cooling and crystallization presumably would entrap the waste within stable silicate minerals of low solubility far below the zone of penetration by water.

Ringwood points out that this waste form (SYNROCK) is more dilute, and therefore, results in a larger volume of waste, which is more costly to prepare and bury. The cost increase would go from the present approximately 0.5 percent (of value of energy produced) to about 5 percent. The advantages are the demonstrated great stability (10^{8} yrs).

Perhaps the most compelling advantage of these materials is that the geologic environment itself has provided the conclusive evidence that these materials will be stable for periods of the order of 10^{8} years.

The immediate geochemical message to be learned from all of this is that the total chemical system will be complex and that whatever forms are selected for the waste, capsule, packing, and backfill, they will need to be in chemical equilibrium with one another and with the rock--in an environment of heat and possible water or steam. Inasmuch as this probably is unrealistic, the total system must be optimized such that the disequilibria are minimal and that reactions proceed in a "favorable" way. Examples are the reduction of permeability through the formation of less-dense minerals that seal the apertures of cracks and intergranular passageways, and the formation of reaction products that are highly sorptive. In experiments by Summers and others (1978), the reaction products that greatly reduced the permeability were also highly sorptive. This would certainly be a desirable and highly favorable kind of reaction. This optimization may require some feedback from the geochemist to the engineer in order for the waste form and (or) the packing and backfill material to be tailored to the hydrogeologic environment.

The prospects appear quite favorable.

Geoeconomics

The criteria of concern here relate to three basic partly interrelated problems:

1. Competetive demands on the site for resource extraction and as a repository.
2. Problems of integrity of the site due to previous exploration or mining.
3. Possibility of inadvertent penetration during exploration in the future.

In an advanced technological society such as ours, there are growing needs for a variety of mineral resources. Because of this, regions of mineral deposits (of value or only of potential future value) should be avoided, not only for this present conflict of demands and possible economic loss of a resource, but also because the presence of that mineral deposit would make the site attractive for mineral exploration in the future--when the presence of buried waste there has been forgotten. Drilling or extracting at that future time could penetrate the waste and expose those future generations to great hazards.

In regions where some mining or oil exploration or extraction has already occurred, there are two problems. One is the penetration during future exploration referred to above--the geologic clues that led to exploration in the past would remain and would likely lead to exploration in the future. The other problem is typified by the previously proposed repository site near Lyons, Kans. Deep exploration for oil and gas resulted in untold numbers of exploratory and "wildcat" holes being drilled. The locations of many of those are no longer known. In addition, active potash mining by the solution method was going on close by--the extent of solution channels was not know. Both of these features posed unknown and potentially serious problems for the site, which was abandoned.

In many places, mineral resources have been mined in sedimentary rocks which cover buried crystalline rocks, or may have been extracted from the crystalline rocks themselves. Many of these were surface strip-mines and open-pit mines, or were shallow underground workings that did not reach or extend appreciably into the crystalline rocks. In those areas, potential sites in those crystalline rocks probably would not have been jeopardized directly by the workings. However, special evaluation would need to be made to determine the effects of the of the shallow workings on the surface and subsurface hydrology, and the likelihood of future exploration that could lead to penetration.

In this category, some people include criteria such as "no present or possible future dams." Existence of dams and reservoirs could readily be determined in a given region. However, "possible future dams" seems to me to be too vague to determine. The problem of dams appears to be twofold: one is the concern about contamination of the reservoir water, the other is the concern about the future course and quality of the water that had drained into the repository. Both pose health hazards.

I view the meaning and relevance of "possible future dams" to be dams that might be built before the shaft was plugged, and that would flood the area of the shaft and surface facilities. Because of the lead time required to plan dams, this likelihood could readily be checked.

The other part of the concern is more a hydrologic one, and is related to that of whether or not it is of concern (a criterion) that sea level may change and inundate the region. This is discussed under "Hydrology" above.

Accuracy of prediction

There are at least three schools of thought as to how isolation can be achieved. They provide a good opening for discussing predictions. Briefly summarized--and probably somewhat overstated--these three views and their rationales are as follows:

1. We must rely on the geologic medium and environment alone (see section "Requirements for Isolation," a-e, p.). The geologic record is a reliable indicator of the geologic future--if a region can be shown to be tectonically stable for tens or hundreds of millions of years, and to contain rocks with very low permeability, we can rely upon its continuing to be so for the next half million years or so. Proponents point out that the geologic record gives them the time leverage which is lacking for the prediction of the behavior for the engineered barriers (such as packing, sealant, backfill, and plug for the shaft). And they make mention of the poor "track record" humans have had for other aspects of the nuclear-fuel cycle. Proponents of this view also point out that the natural repositories, such as uranium are deposits--including at least one that went critical--have adequately contained the radionuclides for millions or billions of years without man's intervention.

2. We must rely on engineered barriers alone[13] ("Requirements for Isolation", f-i, p. 11). Proponents are convinced that the behavior and performance of engineered barriers can be completely characterized and precisely predicted; and that the rates of corrosion of the canisters, dissolution of the waste, and the perfection of sealant packing materials are precisely known and predictable. They claim that these engineered barriers provide a multiple-barrier system that along is adequate. One view holds that it doesn't matter what kind or condition of rock we put the waste in, for the engineered barrier can suffice. One group believes that a barrier such as compressed bentonite can be prepared which provides such an absolute hydraulic seal that water will <u>never</u> reach the canister. Therefore, corrosion and dissolution cannot take place and we need not even consider radionuclide movement in the ground water.

3. We must rely on the combined effects of the best rock medium and the best engineered barriers (the optimum combination of views 1 and 2, above). The rationale of this view is that we must select regions, media, and engineered barriers each of which is optimal and in harmony with the total. This is the position taken by such agencies as the EPA, NRC, and USGS, and is recommended in the IRG report (1978) to the President.

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[13]Views 1 and 2.--Emphasizing whether or not we should rely on activities of man--should not be confused with the view of a large group who believe that we must not rely on the activities of man for long-term <u>monitoring</u> to ensure that isolation is maintained.

The absolute certainties of the behavior of engineered barriers (viewpoint 2, above) are premised on the assumption of an invariance of such attributes as the present composition and pH of the ground water; the present density of fractures, their orientation, and aperture; the state of stress; etc. Inasmuch as all of these can and almost assuredly will change, the degree of predictability of behavior of the engineered barriers drops at least to the level of that of the predictability of the geologic conditions, as follows:

We agree that we probably will not be able to completely characterize the present geologic state of a suitably large rock mass, much less its complicated past geologic history. If the past and present conditions and behavior provide the principal key to predicting the future, then we certainly cannot predict the future with any greater precision. The present state may not be completely known even if we applied such extensive drilling that those drill holes alone would cause any site to be rejected. But, how necessary is it to "completely" decipher the geologic record? Put another way, we must attempt to characterize the geologic conditions sufficiently--not completely. Some attributes are redundant and unnecessary; some data have such high covariance that one serves as a surrogate for the other; and some parts of the record and some attributes of the rocks and the region are not at all relevant to the suitability of the site. It becomes critical to determine what the pertinent pieces of evidence are, and how readily and accurately they can be determined.

Granted, although a lengthly and well-understood record of geologic history at a site provides compelling reasons to believe that the site will be suitable, there is always the possibility of some unforeseen natural event taking place that would jeopardize the safe long-term containment (Bredehoeft and others, 1978, p. 10). These possibilities need not be wild speculations but, in any event, it cannot be proven that something will not happen anymore than we can prove that something will happen before a specified number of years in the future. Although the odds may be extremely small, the consequent risk is extremely great. I hasten to point out that this is true of disposal in any rock medium or disposal by any other method, such as rocketing the waste into the sun or deep space. It is also true at any time during the hazardous life of the waste, starting the very first day the repository is sealed.

In their important paper on earth-science perspectives of the waste-disposal problem, Bredehoeft and others (1978, p. 10-12) discussed geologic predictions. First, they posed the question, "How credible are geologic predictions ranging from 1,000 to 10 m.y. into the future?" They did not specifically answer their own question, and although they lead the reader through a line of reasoning that seems valid and laced with appropriate qualifying statements and caveats, they leave the impression that geologic prediction is not adequate even for 100 years. Their qualifying statements get upstaged by strongly worded conclusions such as (1) radioactive-waste models are ". . . highly complex and unpredictable . . .," (2) there appears to be no clear basis for determining rates of occurrence of geologic events and processes; (3) "observational record of the past, on which estimates of the rates of occurrence of geologic events are made, is invariably incomplete . . ."; (4) "many processes probably can never be modeled precisely . . . and cannot be determined with certainty . . ."; (5) ". . . long-term prediction . . . is unreliable and impossible to perform . . .;" (6) track record in geologic prediction for short time (100 yrs) has ranged from good to poor and may be worse than it appears.

Their qualifying statements become submerged in the presence of such strongly worded conclusions. Even their concluding statement that the inability to predict [precisely] can be offset in part by a multiple-barrier approach seems overshadowed by pessimism garnered from the preceding negative statement.

The overlooked other side of the coin holds out some reason for optimism, for it shows that (in the same order as above):

1. Present models are inadequate principally because we need to acquire more data. However, I believe that earth scientists are misleading the public and themselves in their repeatedly stated or implied need to acquire all data. First, it is not economically feasible to be able to completely characterize the rock terrane and geologic processes and, secondly, not all data are relevent to the problem. What we must do is determine what kinds of data and levels of accuracy constitute a sufficient--not complete--data base for making decisions about suitability. I believe that this is worth repeating.

2. Active contemporary research is providing a clear basis for determining rates of geologic events and processes.

3. Although the record is incomplete, it is being augmented by research (see 1. above, re complete versus sufficient).

4. "Precise modeling" was never anticipated or required so long as we establish and evaluate effects of limiting conditions.

5. Although long-term prediction may not be possible "with high confidence levels," limiting conditions and multiple barriers may still provide satisfactory solutions. If each condition is considered at the "worst case" limit, and if the net effect of all the "worst cases" acting in concert shows that isolation can still be achieved, the site would seem to be highly suitable.

6. The track record cited is misleading in that only poor examples from soil engineering (what relevance does that have for deep geologic disposal?) and from one report on tunnel engineering geology were cited--the numerous good examples were ignored.

Examples of good "track records," even in complex terrane, abound in the literature. Some date back to the very early days of engineering geology (Legget, 1939; 1973, such as the Queens Midtown Tunnel in New York City, and the Catskill water supply project.

In tunnel geology: location of tunnels must be within relatively small geographic confines, and one makes do with the best terrane conditions that can be found there. The tunnels cited in Colorado, for example, had to be driven at specific sites selected for reasons other than geologic conditions. The sites were in complex heterogeneous rocks which every local geologist knew--and any casual visitor could see--were complexly faulted and highly fractured. The geologists knew beforehand that prediction of behavior or performance of the rock mass at a specific position would be tenuous at best. In selecting repository sites, I would like to think that such a region would not have been considered, whether we had the retrodictive tunnel data and experience or not, for the rock structures and relationships at the surface would tell us that those Colorado tunnel sites could not be acceptable as waste repositories.

The present policy (described above) of trying to find suitable sites at the DOE plants--places the selected for reasons entirely different than waste disposal--is akin to the tunnel geology problem and thus may well have similar built-in "traps" for track records.

Perhaps the key to the whole pessimistic tone of the report (Bredehoeft and others, 1978) is the use of the term "precisely" and "with certainty", which are woven through the text and embodied in the telling statement in their concluding remarks: "Earth scientists . . . cannot guarantee future stability." (underlining added). Surely, no scientist or engineer who has thought about the problem has considered even for a moment that we can "guarantee" that any of a number of hazardous geologic events will not occur--not today nor at any future time. For that matter, there is no guarantee that Earth will exist tomorrow--only a certain statistical likelihood that it will. If guarantees are required, we are wasting our time contemplating a geologic disposal concept--or any other kind. Anyone who offers a guarantee deceives himself as well as those who give him their ear.

I completely agree, therefore, with Bredehoeft and others (1978, p. 12) that modeling will never give a single answer to the suitability of a given site to contain the waste; rather a range of alternative outcomes will be provided. The limits of this range will constitute a "best case" and a "worst case." As with everything else in life, there is always a possibility that a given conclusion is wrong. To the extent possible, that risk must be incorporated into the decision-making process.

Important progress in prediction of geologic events has been made in the Nevada Nuclear Waste Storage Investigations (NNWSI) project. For example, careful and detailed studies indicate that the design of a waste facility at the NTS would be limited by natural seismic motion--not ground motion due to testing of nuclear weapons. Further, sites within a few kilometers of a major fault trace might be subject to rock accelerations at the surface of 0.7 g if the fault were to rupture over its entire length ("worst case"). It is calculated that an acceleration of 0.7 g has a return period of about 15,000 years, and 0.5 g has a return period of about 2,500 years. These accelerations attenuate rapidly at shallow depths and would likely be only about one-third of the surface acceleration, or less (Dowding, 1978; Yamahara and others, 1978) The time required for the tectonic character of regions in the southern Great Basin to change exceeds the required isolation lifetime of a repository. The location of a repository site within a structurally positive block, a high-standing granitic pluton, or a caldera resurgent dome probably reduces the likelihood of tectonic and (or) volcanic disruption of such a site to well below the "worst case" probability calculations which are 10^{-8} to 10^{-9} per year.[14]

SITE-SELECTION RATIONALE

An efficient and feasible approach to exploration for selecting sites must be premised on some kind of strategy which relates to the factors of figure 1 and table 2 and that indicates desirable attributes, which can be portrayed in a map form. Each attribute should be able to be weighted in the strategy, in terms of how undesirable a feature can be and still be acceptable. Some features, such as faults or recent volcanism would be weighted such that, no matter whether "good" attributes occurred in the area, the area would be completely rejected. Weighting also provides for a ranking of best, second best, etc. Computer application can readily permit the testing and comparison of alternative strategies, including the consequences of changing certain weights or constraints such as described by Smedes (1975) and Turner and Smedes (1974).

Feasibility requires that the bulk of the exploratory screening or culling be done by data in map format. This means that it must be based on existing data--which are very incomplete and unrealistically time-consuming and expensive to acquire--and on surrogate data that can be readily acquired. These data should be selected and applied in a priority way such that those which already exist or are cheapest to acquire and have likelihood of culling largest areas from further consideration are used first. Each subsequent culling or screening step would involve

[14]These data are from an administrative report: "A preliminary appraisal of impediments to siting nuclear waste repositories at the Nevada Test Site" prepared by the NNWSI Participants (DOE, USGS, Sandia Labortories, Los Alamos Scientific Laboratory, Lawrence Berkeley Laboratories, and Lawrence Livermore Laboratories).

using data that were more difficult/costly per square kilometer to acquire; however, successively fewer square kilometers are involved at each successive step. In this way the method is time- and cost-effective.

Maps of attributes such as those presented in this report provide a beginning for selecting regions. Many others will be required, of course. Strictly cartographic overlaying of photographic positives (desirable attributes) and negatives (undesirable attributes) provides insights into the impacts of generalized preliminary strategies which do not involve weighting of degrees of goodness or badness.

Examples of the effects of different weightings of such a scheme (but applied to a different problem) are shown in Turner and Smedes (1974). A rather harsh example of such an overlay selection is presented here (fig. 14), not to indicate any real priority of factors, but only the method. The overly simplified strategy used was to select all areas where the following conditions were mutually attained (listed in terms of basic maps used, the figure numbers for each map are given in parentheses):

1. Exposed crystalline rocks (5)
2. Igneous rocks (3)
3. There are no mineral deposits (12)
4. There are no occurrences of coal, oil, or gas (13)
5. There are no known recent or active faults (11)
6. There are no earthquake epicenters (9)
7. Probable maximum horizontal motion of the ground surface due to earthquakes in the next 50 years is less than 10 percent g (10)
8. There has been less than 2,000 m of vertical movement in the crust during the last 10 m.y.

Note that it was essential to have drafted and photographed each component of a composite map; that is, each of the three categories that were combined to make figure 3 were compiled and photographed separately. The same is true for the horizontal-motion data of figure 10.

A more realistic way of dealing with mineral deposits (for example) would be to give them a low weight but not entirely exclusive. In that way, an area would be "flagged" as having some likelihood of containing mineral deposits. Inspection of detailed maps of mineral deposits would then indicate whether they were at the site, too close to the site, or far enough away to permit acceptance of the site at that stage of screening.

There are various degrees of uncertainty in some of the site conditions even before disposal activities begin. In addition, there are degrees of uncertainty that an event will happen and, subsequently, what its consequences will be. Evaluation of each uncertainty generally will not give a precise answer but rather a spectrum of choices (Bredehoeft and others, 1978),that is, a range. If we wish to be certain of the maintenance of the integrity of the site, we should consider a site evaluation which uses a "worst case" approach. That is, each attribute or likelihood of an undesirable event is accepted at its worst value, such as assuming that water will reach and dissolve the waste the day after the repository is closed, etc.

A more realistic way of dealing with the problem regionally (before site-evaluation state) is to assign appropriate weights to each good and bad attribute. In that way regions or areas would not be automatically rejected because of some likelihood that they were tectonically active or contained faults or mineral deposits, for example. Instead, they could be rated as less worthy of a detailed examination than similar areas where such attributes are known or thought to be absent, or flagged for examination of detailed maps and data to see if they did indeed possess those attributes. As described above, many suitably large sites may well be available within regions, which because of available data and (or) scale, must be shown on the maps as tectonically active or as containing mineral deposits. A site-selection screening procedure should not reject these regions permanently, but should "flag" them. The reverse is true also--some areas presently shown as having favorable attributes may, on detailed examination, turn out not to be favorable.

CRYSTALLINE ROCKS VIEWED IN TERMS OF CRITERIA FOR ISOLATION

General

Crystalline rocks make up more than 90 percent of the crust of the continents. Their approximate known distribution in the U.S. is shown on figure 3 where they are subdivided into igneous rocks, metamorphic rocks, and Precambrian metamorphosed lavas. To the extent possible, only the granitoid rocks are shown. Although the entire continent is underlain by crystalline rocks at some depth, in many places that depth is too great to be of interest at this time because of the present specification that a repository be about 1,000 m beneath the surface.[15]

A more detailed but extremely incomplete lithologic map of the entire U.S. can be prepared only by very costly and time-consuming reevaluation of the rock from thousands of deep drill holes and tedious compilation from large-scale maps. At this stage of characterizing the entire U.S. as a step in the exploration of sites, the map of figure 3 is sufficient.

The approximate mineral and average chemical composition of the principal types of granitoid igneous rocks are shown in table 3. Although the abundance of the different types of metamorphic rocks is not known, the exposed granitoid igneous rocks are predominently granite and granodiorite. Diorite and gabbro comprise only a very small part. The volume of quartz-free and quartz-poor igneous rocks--such as syenites and monzonites--and of feldspathoidal rocks probably is less than 1 percent of the total of all those exposed (Daly, 1933).

Crystalline rocks are areally about as extensive in exposed masses as salt and shale individually are in total extent--exposed and in the subsurface. This relation is shown in the widely published generalized maps of figure 4 which give the misleading impression (previously refuted by Smedes, 1978, p. 100-101) that available areas or volumes of the different rock types are about equal. The true representation of the volume of crystalline rocks is portrayed by their distribution in three dimensions. This is shown at the national level by figure 5 (which is a more detailed map of the extent of exposed crystalline rocks than is shown on figure 4); and by figures 6 and 7 which indicate the general distribution of crystalline rocks at several increments of depth.

By comparison of these generalized data (figs. 3, 6, 7) it is clear that there are enormously greater volumes of crystalline rock available for consideration as potential waste repositories than there are for salt or shale--or for volcanic tuff or lava. In addition, vast areas of these crystalline rocks are exposed at the surface (fig. 5) where their physical and chemical properties can be more completely and precisely determined than can rocks which occur

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[15]Although this depth is somewhat arbitrary, it was selected partly on the basis of a judgment of the depth that probably would be safe from collapse and from surface phenomena such as erosion, meteor impact, fire, and flooding. Greater depths obviously require more costly excavation.

principally in the subsurface, as do salt and shale. Extensive data (potentially available) from these exposed rocks will enable us to predict more accurately their nature at depth. However, these data do not presently exist in a significant amount or for any appreciable extent for any of the rock types.

Many decades of research on mineralogic, chemical, rock-mechanical, and other properties of crystalline rocks have produced a published record that is prodigious. There is an extensive experience of fieldwork by many people over many years, but there are no overall summaries of that prodigious research specifically prepared for waste-management studies. Even though this literature and experience constitutes just bits and pieces of the total complex problem, they indicate that the principal rock types and large masses of crystalline rocks can be characterized in terms sufficient for a general overview such as this, and that the smaller masses and, especially, the sparse and unusual kinds of rocks, range so widely in their physical and chemical properties that they may reasonably be rejected at this stage.

The most uniform presentation of the distribution, type, and structural relations that presently exist in large areas is that of the various State geologic maps, whose scales generally are 1:500,000 or 1:250,000. To go beyond this general small-scale overview of these rock masses requires an exhaustive library research which at best shows only a very incomplete and inconsistent data set. In a beginning attempt to characterize major crystalline rock terrain in terms of suitability for repositories, we (my colleagues D. J. Gable and C. T. Hatton, and I) used the most recent and detailed data available, but eventually were faced with the following conclusion: virtually no crystalline rock body has been sufficiently studied so that we were able to characterize it adequately or to even be able to compare it directly with another body. This is largely due to the fact that geologic research conducted in the past was for objectives that had no close relation to the data needs of the waste program and were not multidisciplinary in scope. That is to say, there is no precedent for the kind and quality of data needed for studies of nuclear waste disposal. As examples, one region was mapped and studied in great detail for purposes of structural history, but petrology and geochemistry were virtually disregarded. Even the structural studies do not give appropriate, if any, data on the spatial frequency of joints, their apertures, and the types and ages of minerals that coat their surfaces. Another region was studied petrochemically but not structurally (in detail). Rock-mechanical studies rarely involve detailed petrochemical or isotopic studies; and so on. In short, the data are so incomplete and inconsistent over short distances, that a coherent summary picture of the conditions relevant to disposal studies cannot be obtained without further comprehensive and highly detailed field and laboratory work.

Because this approach is not feasible, other approaches will need to be taken in the exploration for sites. One approach is that of the concept of surrogate data described in a following section.

A further gap in our knowledge is brought to light by the data in a recent comprehensive report in which candidate sites were selected in crystalline rock terrane (Murrie and Gates, 1979). The selection system involved rating attributes, and summing the total. A "good" attribute was rated +1, a "bad" attribute was rated -1. Those for which there are no useable data were rated zero--neither good nor bad. Even though hydrology was acknowledged by them to be the prime criterion, no useable hydrologic data were found and all regions and sites scored zero for hydrology. In effect, hydrology was not a criterion! Clearly, when hydrologic data are obtained, the ranking of areas could be turned completely upside down! Surrogate data clearly are needed here.

The readily available, small-scale, and incomplete data referred to above, plus some of the topical "bits and pieces," were used in preparing the following general description of the likely behavior and suitability of crystalline rocks and rock masses. This follows the same order as the criteria, listed above.

Geometry

Although some crystalline rocks occur in small or thin bodies such as dikes, sills, and laccoliths, many are hundreds or thousands of square kilometers in areal extent and 10-40 km thick. Clearly, these larger masses (figs. 3, 5, 6, 7) and many lesser ones, fill the requirement of being "deep enough . . ." and, depending on their hydraulic conductivity, "large enough . . ."

The petrologic and petrochemical homogeneity is rather well known for only a relatively few "classical" areas such as specific single plutons or coalesced masses of plutons that constitute batholiths (the Sierra Nevada batholith in California or the Boulder batholith in Montana). However, the nature of their rock-mechanical, fracture, and permeability properties, much less their degree of mechanical homogeneity, is scarcely known at all. For the vast majority of igneous plutons or masses of metamorphic rocks, neither the petrologic nor the physical homogeneity is known, not even in a very reconnaissance way.

Joints (fractures) are almost universally proclaimed to be the determining hydrologic factor in crystalline rocks. If so, it will be important to know the locations of lower spatial density of fractures, of less-continuous fractures, and of the least intersections of fractures inasmuch as all of these would affect the hydraulic conductivity of the rocks. These data belong with the geometry and stability criteria, but will be treated completely here. To determine these parameters by detailed field measurements of large terranes in site-selection exploration would not be feasible at all. However, it may well be that the least-fractured or least-jointed zones could be identified by analysis of lineaments on images from spacecraft. If there is a correlation between the relative spatial densities of lineaments derived by analysis of spacecraft images and the densities of fractures in the rock, this image interpretation becomes an important explorative tool.

The covariance among densities of lineaments at the scale of spacecraft images (1:1,000,000), aerial photos (1:50,000), and the detailed maps of the joints themselves (1:1,000 or larger) must be established. The other end of the scale of fractures is important also. Microscopic and submicroscopic fractures are of interest because of their influence on such things as matrix permeability, chemical reactions, rock stress, geophysical properties (Clark, 1966, p. 196; Swolfs, 1976; and Simmons and others, 1978) and as a potential indicator of proximity to faults. They also provide clues to the deformational history of the rock mass. However, these microfracture data are expensive and time consuming to acquire.

For these reasons, we are conducting a study to determine the nature of the covariance among the megafractures (from Landsat image), macrofractures (from aerial photos and field mapping) and microfractures (from laboratory study of selected samples). It seems prudent to establish this before much time is spent in detailed mapping of fractures or in selecting sites without first knowing that the rocks there are the least-fractured. It is potentially even more important to determine the vertical inhomogeneity of the joint or fracture system. Again, before time is spent in detailed mapping of joints at the surface, it seems prudent to establish whether there is any correlation between those and fractures at depth.

Serious doubts exist about this depth correlation, per se. For example, a recent report (Witherspoon and others, 1979, p. 8) shows that the granitoid igneous rock at the Stripa Mine in Sweden has joints whose surface orientations bear no similarity to those in tunnels about 338 m below the surface. I suspect that the stress orientations which produced the joints varied over short distances due to the fact that the site is in the irregularly shaped roof contact zone of the granitoid rock. Even if this lack of similarity is representative of many rock masses, it still remains to be determined whether there is a correlation between spatial frequencies (but not attitudes) of joints, of microfractures, and of the rock fabric (foliation, flow banding, and other preferred orientation of minerals). Much remains to be learned.

Stability

The strength of all rock types increases with confining pressure and decreases with rising temperature and time; however the magnitudes and rates of the effects are different for different rock types. Although each class ranges widely, on the average, granite and other granitoid igneous and metamorphic rocks above greenschist facies differ from sedimentary rocks by having: (1) strengths which are affected less by temperature, (2) nearly twice the ultimate strength, and (3) about four times the crushing strength (Clark, 1966, tables 11-3, 11-4; Vutukuri and others, 1974).

By virtue of these generally superior strength relations, crystalline rocks will pose fewer engineering problems of excavation for repositories, provide for greater integrity of the chambers during the active life of the repository, insure greater likelihood and ease of retrieval of the canisters of waste if that should become necessary at any time, and result in a lower likelihood of subsidence after closing the repository.

The possibility of unreconcilable deformation, collapse, or other traumatic mechanical failures of the rocks during the active life of the repository (while it is being loaded), and later, is vastly higher for salt and shale than it is for the majority of crystalline rocks. The specific state of stress in certain rock masses results in rock bursts and other modes of failure during and after excavation. Thermal stresses superimposed on the rocks by the waste may result in further susceptibility to failure. Advantages of certain crystalline rock masses accrue from the fact that (a) they are large and sufficiently homogeneous such that their behavior is relatively uniform and predictable, and (b) there is an unexcelled wealth of research and experience in the mining engineering in such terranes--we know how to determine the behavior and to design the excavations to accommodate and minimize the rock failure.

The superior strength of crystalline rocks should enable them to experience unpredicted increases in seismicity and tectonism without their performance and behavior necessarily being adversely affected.[16]

Facts in support of these statements, which relate the data from laboratory measurements of samples of rock (1-3, above) to large masses of rock in the terrane are:

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[16]This is known to be true for rock specimens, however, the premise is contested as it pertains to rock masses. See p. 48.

1. Deep underground workings in mines in crystalline-rock terrane are known to have remained open and unimpared for many centuries (for example, Wendt, 1891). Some of these are networks of tunnels not unlike those planned for repositories. Some are large chambers or vaults tens of meters in width and height which are known to be intact after decades.

2. In places, crystalline rocks have been extensively excavated to provide large underground space for many purposes. Sweden, especially, has taken advantage of this great strength. They use large underground excavations, with or without reinforcement of the roof and walls, for a variety of things such as an underground drydock large enough for destroyers (Legget, 1939), water treatment plants, and a number of enormous bomb shelters which are used for underground parking in peacetime (Albert, 1961). These large excavations have an undisturbed rock roof whose minimum thickness is 15 m (some have 30 m or so). They are designed to be strong enough to remain intact should any buildings on top of them collapse, and to be safe against a 1-megaton bomb at a distance of 1,000 m from the site of the blast (Albert, 1961, p. 67).

3. Large unlined chambers have been successfully used for storage of natural gas, hot water, hot oil (Sweden), water for pumped storage, compressed air, and liquid petroleum products for long periods of time in such countries as the U.S., Sweden, Finland, Norway, Scotland, Switzerland, and Portugal (Bergh-Christensen, 1978; Bergman, 1978; Bjurström, 1978; Einstein and others, 1978; Farquhar, 1974, p. 41-45 and 1976; Milne and others, 1978).

4. The roof and floor of some underground tunnels in bedded salt at the Lyons, Kans. test facility had severely buckled inward (toward each other) during the few years duration of the testing (W. McClain, 1976, oral description of photos). In fact, it was concluded that during some of the development, the openings would close by rock creep so rapidly that the rate of development (excavation) of chambers would have to be matched closely to the rate of waste emplacement so that sufficient clearance would remain for emplacement vehicles (Koplik and others, 1979).

Because the presence of fractures (joints and other discontinuities) increases the hydraulic conductivity of a rock mass, the probable depth of extent, spatial density, orientation, aperture, and degree of connectivity of fractures is of vital concern for waste repositories. Further discussion and critique of fractures is presented in the section on "Hydrology" below.

Most crystalline rocks formed or were emplaced deep beneath the Earth's surface where the weight of overlying rocks--the lithostatic pressure--was great. Upon cooling, these deep-seated masses apparently acquired large locked-in internal stresses which formed in response to and in equilibrium with the lithostatic load. Data of Lee and others (1979) suggest that rock masses emplaced during tectonism tend to have come into equilibrium with higher stress than did the posttectonic masses which were not influenced by these additional regional compressive stresses. As a result, the horizontal compressive stresses in the syntectonic crystalline-rock bodies increase with depth at rates far greater than can be accounted for by the rock load (Lee and others, 1979). Decompression by erosion may account for excessive horizontal stresses in places. Although this one example (Lee and others, 1979) scarcely constitutes a trend, such conditions are probably commonplace (H. S. Swolfs, oral commun., March 1980).

When uplifted and then exhumed by erosion, these deep-seated rocks tend to adjust to the decompression brought on by erosional unloading (Ollier, 1969) by relief of the vertical component of stress (Varnes and Lee, 1972; Lee and others, 1979). This relief is most active at the surface and diminishes but propagates inward (largely downward); it tends to produce sheeted joints parallel or subparallel to the changing erosion surface. In pretectonic or syntectonic rock masses, and in areas where there has been subsequent regional tilting or warping, the accompanying stresses may result in steep fractures as well. The rate of relief of stress is a function of the elastic, frictional, viscous, and other time-dependent properties of the rock, and may be retarded by such properties as the interlocking fabric of anisotropic mineral grains variations in stiffness, and cohesion among mineral grains. The rate may be increased by the chemical effects of water (Lee and others, 1979).

Lee and others (1979) have pointed out an important problem encountered in attempting to determine the in situ stress in rocks at or near the surface. They found that in both a syntectonic and posttectonic granite in Maine the maximum horizontal-stress directions rotated clockwise at shallow depths, becoming aligned with major faults of the region which are younger than either granite. Similar relations were observed in Colorado (Lee and others, 1976). It is not known whether these two examples are representative of the behavior of most crystalline rock, and the data may be subject to other interpretations. These examples do serve to point up the problems to be solved, however, for this means that data on stress directions in rocks--admittedly sparse--may not really indicate the in situ stress directions that will exist at repository depths.

Clearly, the in situ stresses and their effects need to be known in order to evaluate the suitability of the site and, subsequently, to design the excavation for minimum hazard of rock bursts and related traumatic stress-relief phenomena.

Tectonism

As described earlier, crystalline rocks in different regions or settings have widely different degrees of strain as shown by the fabric of the rock and, under the microscope, in the component mineral grains. This both affects, and presumably can be detected regionally by, changes in geophysical properties (such as seismic velocity) of the rocks.

The apparent existence of striking differences and ranges in magnitudes and orientations of residual stresses interpreted from measurements in syntectonic versus posttectonic crystalline rocks, leads one to question seriously the concept of transfer value of data. "There are granites and granite" (Read, 1948, p. 1); i.e., much of what is learned in Nevada probably will not apply to Wisconsin; data from Sweden probably will not apply to Japan, and so on. This awareness and the discussion above, make it desirable to use as a first characterization the tectonic setting of the rock mass (see table 4). The importance of this consideration is shown by the close relationship among tectonic setting (table 4), degree of tectonic stability (fig. 2), earthquake loci (fig. 9), and seismic vibration (fig. 10).

The thermal history of crystalline-rock terrane can be established by isotope methods such as Rb-Sr, K-Ar, U-Pb, and fission track studies. Knowledge of the "closure" temperature of these systems as a function of host minerals allows reconstruction of thermal histories that can be translated into rates and magnitudes of uplift, denudation; and tectonic stability (Peterman, 1979; Peterman and Hildreth, 1978).

Natural isotope systems show that crystalline rocks in the shield and stable upwarp areas (1A and 1B, table 4) have been stable for more than 1 b.y. An exception is the Adirondack Mountains (1A) which is presently rising rapidly (Isachsen, 1975; Isachsen and others, 1978);

Table 4.--*Examples of crystalline-rock terranes classified by age and tectonic setting. The geologic characteristics of these terranes are sufficiently different to warrant studies of several representative classes*

I. Regions of Precambrian Crystalline-Rock Terranes

- A. Shield areas
  1. Lake Superior region
  2. Adirondacks
- B. Stable regional upwarps
  1. Southeast Missouri
  2. Llano uplift
- C. Shallow buried basement (mainly midcontinent)
- D. Tectonically exposed Precambrian
  1. Appalachians
  2. Rocky Mountains
  3. Basin and Range
  4. Wichita and Arbuckle Mountains

II. Regions of Phanerozoic Crystalline-Rock Terranes

- A. Areas within Precambrian Crust
  1. New England
  2. Appalachians
  3. Rocky Mountains
  4. Basin and Range (in part)
- B. Areas Marginal to Precambrian Crust
  1. Cordilleran batholiths (in part)

its rocks are pervasively shattered. either by tectonism or by decompressive relief of stress accomplished by erosional unloading. Some Precambrian crystalline-rock terrane has been tectonically uplifted and exhumed by erosion (1D, table 4). Depending on the nature of this uplift and the proximity of the rocks to the bounding faults (domain boundaries) some rocks are in equilibrium and hydraulically sealed whereas others are not (Z. E. Peterman, unpub. data).

Crystalline rocks within some of the major blocks in the Precambrian of Wyoming have not undergone major tectono-thermal events in the last 2.5 b.y., as shown by undisturbed isotopic systems in the constituent minerals of the rocks. Peterman and Hildreth (1978) were able to determine that a major tectonic event took place in central Wyoming about 1.5 b.y. ago. The block south of a major fault zone was uplifted and cooled through the 300°C isotherm, as registered by K-Ar ages of biotite in the rocks. The uplift was of the order of several kilometers. As the minerals passed through their "closure" temperature of 300°C, the radioactive clock was set in motion--about 1.5 b.y. ago. Rocks on the north side had already passed upward through the 300°C isotherm of the Earth's crust some 800 m.y. earlier.

A difficulty in assessing tectonic history and stability of large homogeneous masses of crystalline rocks is the fact that by their homogeneity they do not afford any (or many) marker units whose offset would be the conventional means of determining locations of faults. Geophysical techniques (sonic, radar, electrical methods) can assist greatly in determining if and where faults exist in these rock masses.

Once faults are found, by whatever means, it is desirable to date their time of most-recent movement. Many methods will need to be considered, depending on the specific case. Geomorphic analysis may serve. Dating of unbroken minerals which have filled the aperture or coated the surfaces of the fault can be done by isotopic methods. Travertine and related deposits commonly fill or cover the fault; they can be dated by using the uranium-series method which is useful far beyond the range of ^{14}C (U.S. Department of Energy, 1979).

As noted earlier, we probably don't know the locations of many of the active and recent faults. The only published map that shows the state of this knowledge is that of Howard and others (1978) shown as figure 11 of this report. A revision and update of that map is included as part of the data base accompanying the maps of vertical movement in the report by Gable and Hatton (1980). In addition, the map of earthquake epicenters (fig. 9) and microseismic surveillance of potential sites give clues to areas where faults probably exist.

In general, our predictive capabilities are well-enough established by geologic, geomorphic, and geophysical methods that the likelihood of a fault actually cutting the repository is negligible and hence of little concern in many regions. Our main concern is about other tectonic events such as tilting or warping--which generally are less easily determined in crystalline-rock terrane--and, which along with faulting, may affect the regional joint or fracture system and the ground-water system. To the extent that this may adversely affect the hydraulic conductivity, it becomes a matter of principal concern.

The presence of volcanic and other young igneous rocks and features is generally well known (summarized by Luedke and Smith, 1978a, b), and can readily be determined in specific areas by conventional field mapping and geophysical surveys. If a site is proposed in terrane where such volcanic features occur, it is imperative that the likelihood of volcanism be carefully evaluated. Volcanism is cyclic only to a certain point; then it ceases or becomes episodic. For example, in southwestern Montana, igneous activity occurred in Precambrian (Belt Supergroup) time and then not again until Late Cretaceous time. In other places, magmatic activity has gone through a distinct differentiation history, closing with irruptions of peraluminous rocks. Before that stage in the differentiation, renewed volcanism can be expected (at intervals of tens to hundreds of thousands of years); after that stage, volcanism is far less likely to recur in the time span of concern. Other factors such as heat flow and geophysical data will help evaluate this likelihood.

The significance of the boundaries of the structural domains described earlier is that it is along them that most subsequent earthquakes are apt to originate, by way of tectonic adjustment. These boundaries also tend to be sites of transport of magma to the surface and of principal movement of ground water in crystalline-rock terrane. These domains can be more readily detected in crystalline rocks by patterns of the aeromagnetic data (P. K. Sims, oral commun., 1968) than in other rock terranes, and by application of isotope data (Peterman, 1979). The size and location of many of them are shown on the nationwide lineament map (Carter, 1974) and by numerous small-scale published aeromagnetic maps.

Because of their great strength and homogeneity, crystalline rocks tend to act as large competent buttresses which do not take part in folding at the structural levels we are considering. Orogeny, and the folding produced thereby, develop and evolve so slowly that they can be considered as not posing any threat during the hazardous life of the waste, unless the waste is placed in presently active orogenic zones, including placement within subducting plates.

Many of the large exposed masses of crystalline rocks in the western States presently are the sites of high rugged terrane. These areas would have lower priority--other factors being equal--because the hydraulic gradients are steep and because of the likelihood of the waste being exhumed by erosion.

Hydrology

Hydrologic containment being the prime criterion, hydrologic conditions are of utmost importance. However, they tend to be elusive, especially with the constraint of very limited exploratory drill holes. The ways of determining these conditions have largely been by other geotechnical attributes, as discussed at length elsewhere in this report.

The hydrology of media such as a crystalline rock poses problems not dealt with in earlier days of "classical" hydrology, for that basically was aquifer hydrology. In that usage, most crystalline rocks were considered to be "impermeable." Crystalline rocks posed problems in that they did not contain a water table in the conventional sense, the water being confined to fractures, and the depth to this water being highly varied and erratic.

Because flow of water in most crystalline rocks will be governed by the presence of fractures, it is instructive to review what the behavior of fractures will be in a repository area. A generalized and necessarily highly oversimplified (and untested) scenario of the physical behavior of the rock mass at a repository is as follows:

Regardless of whether there are preexisting fractures, there will be extensive underground openings whose presence, alone, will create free faces towards which the stresses locked within the rock will tend to be relieved by development of fractures. It is possible that, under certain stress conditions, these fractures would propagate outward over a period of time, and affect a zone of rock around the original repository excavation. Proper design of the excavation--considering such conditions as tunnel diameter versus tunnel spacing and the virgin state of in situ rock stress--may minimize this fracturing (Apps, Cook, and Witherspoon, 1978).

Heat from the waste, after it is emplaced in the repository, will be conducted outward, eventually affecting a zone of rock several hundred meters away. Rock of the repository and in the peripheral heated zone will be under increased compression compared to the virgin state of stress. The rock around that zone, farther out, will be in a state of increased tension (Neville G. W. Cook, oral commun., 1980).

If the repository and the waste package are not designed properly, these changes in stress within the repository and peripheral rock zones could result in the development and propagation of fractures, and consequent increase in permeability. Proper design would ensure that the magnitude of the thermal pulse is below that which would cause fracturing. Under proper design, hydraulic conductivity would be reduced in the zone of compression and increased in the zone of tension.

In spite of engineered barriers and backfill designed to accommodate the effects of fracture growth, a "worst case" conservative approach is to conclude that within the perimeter of the enlarged zone of disturbance, the strength of the rock will have been reduced. Bulk permeability of the rock mass can be assumed to have been so greatly increased that it can no longer be relied upon to serve as an effective barrier to movement of ground water and radionuclides. It is outside this perimeter that there must be a sufficient vertical and lateral extent of undisturbed homogeneous rock of low permeability to provide a flow path that is long enough and slow enough to retard the flow of the radionuclides during their hazardous life. In effect, we simply change the position of the starting point for the long flow path from the periphery of the repository to some new periphery at some distance outward.

The size and configuration of the repository cavity, the properties of the rock, and the volume and thermal output of the waste will all affect the relative rates and magnitudes of stresses caused by the two different effects (in situ versus thermally induced stresses). This, in turn, may strongly influence the resulting development of fractures. For example, if fractures created by the excavation are propagated slowly outward from the cavity, the increase in compressive stresses caused by thermal expansion may balance the in situ stress relief and retard the development and propagation of those fractures.

In this natural system of interdependent processes and conditions, the permeability of rock outside the perimeter of disturbed rock referred to above, will both affect and be affected by many items of the "shopping-list" which is so familiar by now. Especially pertinent are the nature, magnitude, and duration of those thermal and physical stresses just mentioned. Those in turn, are functions of such things as the temperature of the canister, the rock type and its original strength and in situ stresses, the tectonic setting and structural history of the area, the shape of the repository and its orientation relative to primary rock fabric and stresses, depth of the repository, presence and gradient of water, and the effects of numerous possible chemical reactions. The effects of these reactions on the strength and permeability of the rock take us full circle back to the beginning of the list.

Research currently being conducted by Atomic Energy of Canada Limited (AECL) has developed an approach to estimating how the stress disturbance from the combined effects due to the vault and to the heat will affect the development and propagation (growth) of fractures (Wilkins, 1979). The approach shows how slow crack propagation in rock may be quantified statistically by the use of linear elastic fracture mechanics, and how the results can be used to define a volume of rock enveloping the repository outside of which no significant fracture development will occur (due to those two causes) during the long time period of interest. Comparable studies are being made in Sweden (Ccok, 1978).

These induced fractures will have a potentially profound effect on the hydrologic behavior of the rock masses--hence on their ultimate suitability as repositories.

Although important new data and relationships are being developed in Canada and by the Swedish-American Cooperative studies referred to above much is yet to be known--including the testing of the brief scenario sketched above. The amplitudes of the processes--indeed, the processes themselves--are largely unknown. This field of study seems to be deserving of prompt accelerated research.

To the extent that fractures caused by heat are coeval with those caused by the excavation alone, thermally hot waste may not pose special additional problems, relative to rock stress. However, as mentioned above, the magnitudes, rates, and spatial relations of the two processes (stress induced by the repository cavity and by heat from the waste) and their induced fractures are not known. In addition, the heat may well provide other problems by boiling of pore water in the rocks or by creating buoyant forces that would cause an upwelling to the surface of any water that enters the repository (LBL, 1979).

Two well-known conditions of crystalline rocks appear to have been used contradictorily--to the extent that they have held back the development of programs for use of these rocks in waste disposal. On the one hand, it is a universal characteristic that crystalline rocks are well jointed at the surface. Some assume that this condition continues to depth. On the other hand, it is well known by observation, mining, drilling, and reports, that the frequency, length, and aperture of these fractures diminish and (or) become hydraulically closed with depth (earlier reports are cited by Carlsson and Olsson, 1978; among other reports are those by Yardley and Goldich, 1975; and Montazer, 1978).

Because water is restricted to the fractures in crystalline rocks, water yield and depth should be related, according to the above data. It is, in fact, a relationship known to well-drillers experienced in crystalline-rock terrane, that if water has not been reached by a depth of 600 feet, it probably never will. The now classical reports by Davis and Turk (1964) and Snow (1968) give an even-more solid base to this empirical relationship.

Contemporary work at the Stripa Mine in Sweden and at several other field sites, confirms the same pattern. At depths of only 500-800 m (1,600-2,600 ft) the overall frequency of fractures diminishes and the overall permeability approaches the value for matrix permeability. At depths of less than 400 m the rate is less than 1 km in 10^6 yr (Lundström and Stille, 1978).

Yardley and Goldich (1975) and Yardley (1975) reported that, in a number of mines in the Great Lakes region, the aperture of fractures and flow of water in them diminished with depth. Many fractures were hydraulically sealed at depths of 2,500-3,000 feet.

I have observed drill core from posttectonic granitic masses (near Crested Butte, Colo., 1979) that showed no open fractures below about 1,500-2,000 feet. Fractures that had formed during consolidation and contractions of the magma were filled by late-magmatic aplites and related felsic differentiates or by deuteric minerals. Steep tension fractures that formed later, probably by regional uplift, were filled with minerals such as chlorite, quartz, calcite, and zeolites. The drill core from these holes had to be broken with a hammer in order to fit in the core boxes. The near-surface open joints probably were formed by decompression as a result of erosion, as described earlier in this report.

In summary, facts and relations which suggest that some crystalline rocks in some areas may be hydraulically closed at depths which are reasonable for a repository are:

1. Mines with hydraulically sealed fractures at 2,500-3,000 feet.

2. Asymptotic drop in water conductivity with depth in water wells and other drill holes.

3. Dry unfractured rock in many drill-core sections.

4. Age of ground water increasing with depth.

5. Geophysical data showing that some rocks are "dry" at depths of a few tens of meters (Strangway, 1978) to a few hundred meters (Strangway and others, 1978).

6. Isotope data indicating equilibrium of natural uranium-decay systems which could not be so if water had penetrated freely. In most crystalline rocks, a large fraction of uranium is concentrated along grain boundaries and in unstable minerals, is highly soluble, and is thus susceptible to movement as a consequence of fluids migrating through the rock. Thus, U-disequilibrium studies provide data on the effects of fluid migration during the last 250,000 years. Studies of U-Pb systems in whole-rock samples will provide data to assess the long-term impermeability and hydraulic closure of large masses of crystalline rocks. Some bodies of crystalline rocks are already known to be in U-isotopic equilibrium, hence closed to the movement of fluids. These rock masses deserve special study, and search for additional equilibrium rock masses should continue.

In spite of these data, many people still hold that crystalline rocks at repository depths will be fractured, even prior to excavation, and that fracture permeability will be the mode of flow. As a result, virtually all of the permeability research for the total repository system in the U.S. and much of it in Sweden and Canada is directed at modeling the flow in a fractured medium. This thesis dominates the design and conduct of experiments at the Stripa Mine in Sweden. It has pervaded the several workshops and symposia in the U.S. that dealt with crystalline rocks.

The question of whether crystalline rocks contain open and interconnected fractures at depth is crucial for modeling fluid flow in the vicinity of a radioactive waste repository. An early test to determine whether such fractures are present or not should be conducted at a crystalline rock locality which is typical of the homogeneous masses that might be considered for a repository. Subsequent research should be guided by the outcome of this test.

Geochemistry

The physical, geochemical, and thermodynamic behavior of igneous and metamorphic rocks and their mineral assemblages is well known through extensive laboratory and related field studies. Continuing research is refining and further extending earlier pioneering studies.

Crystalline rocks formed in a high-temperature environment and consist largely of silicate minerals (table 3) whose temperature stability range is far greater than that which will be encountered in the repository.

The nature of likely chemical reactions of these rocks with water--hot or cold--is quite well known and predictable. What is not well known is the nature of the reactions of the rock with the waste. The composition of the waste form has not yet been fully established. Although studies of salt and basalt are underway, virtually no data exist on the kinds of reactions and reaction products of the common rock-forming minerals with any one of the components of the waste, much less with all or combinations of the nuclides in the waste, and the chemical complexing that will occur over time in the ground water.

Among the many complex and largely unknown variables which will need to be studied are:

1. Complete understanding of the natural geochemical systems as they exist before any disposal activities; this could be a very long list.
2. Differences in amounts and solubilities of nuclides in the waste.
3. The rate of dissolution of the canister.
4. The resulting continually changing reactions of waste, canister, water, and rock.
5. Differences related to time of these reactions in relation to changing temperature of the waste; and the thermal effects of the reactions.
6. Continually changing composition of all phases.
7. Affects of the above on the strength of rock and its permeability.
8. Original amount, distribution,and sorptive properties of minerals and their change (capacity, sorption versus desorption, exchanging of sorbed ions, etc.) with time due to reactions.

A remarkably clear and comprehensive statement of this part of the repository problem is presented in the LBL symposium proceedings (1979, p. 147-190). If the brief "shopping-list," above is not convincing that this part of the repository problem may be the most complex, the LBL report surely is. I cannot imagine a more complex chemical and thermodynamic situation than this, if the waste should become dissolved during its hazardous life. That would make all other parts of the disposal system seem like "kid stuff"!

As complex as these geochemical processes and conditions could be in crystalline rocks, at best they are equally complex, dynamic, and uncertain to predict for any other rock type. The advantages of crystalline rocks for repositories, in terms of geochemistry, can be claimed because of (1) the high degree of understanding of the chemical and thermodynamic behavior of the rock mass itself before any communication with the waste; (2) high degree of homogeneity, which affords a simpler hydrochemical system before communication with the waste; (3) higher temperature range of stability--heat from waste, with or without the presence of water, will pose far fewer problems with crystalline rocks than with salt, anhydrite, or shale; (4) greater strength, to withstand any weakening effects of the chemical reactions; and (5) large size, coupled with low permeability to afford a longer, yet slow, flow path.

The fact that these rocks are composed of several different silicate minerals may at first make it appear that crystalline rocks are chemically much more complex than are salt and shale. However, as more information is being gathered from in situ studies of salt and shale, it is seen that they are comparably complex. In salt, there are great variations in properties of halides, sulfates, carbonates, borates, and nitrates, and of different cations--Na, K, Mg, Li, and Ca. Clay is common; brine pockets are present but largely undetectable. Shales range widely in proportions and kinds of clay minerals, and nonclay particles; are strongly affected by thin bedding and partings; and have highly variable water content.

Geoeconomics

Most metallic mineral deposits such as Pb, Zn, Mo, Au, Ag, etc. occur principally in crystalline rocks, whereas deposits such as phosphates, potash, borates, coal, oil, and gas occur in sedimentary rocks. However, many large masses of crystalline rocks and of sedimentary rocks are barren.

In general, crystalline rocks have some advantage over the sedimentary rocks because the sedimentary rocks such as salt and shale (a) tend to be interbedded with other rocks which may be potential resources, such as potash; or (b) are sufficiently thick only in deep structural basins where oil and gas tend to occur, and which may be tectonically active.

RECOMMENDED RESEARCH

Research should continue on every facet of the problem of the long-term behavior of rocks and terrane masses. Of all the studies required, only a few will be specifically mentioned here. Those were selected because they are either milestones whose results will guide future research, techniques only recently applied to this problem, or techniques not yet applied to this problem but whose potential seems great. All of these have been referred to in various degrees of detail above; they are reviewed and summarized here, as follows: (1) in situ research facilities, (2) depth relations of fractures and permeability, (3) isotope studies, (4) microfractures, (5) surrogate data, (6) geophysics and rock mechanics, and (7) natural examples.

In Situ Research

Most of the research to date has consisted of bits and pieces as indicated by the following oversimplified account: One researcher makes laboratory measurements of matrix permeability of crystalline rock "A," another makes laboratory measurements of the moduli of elasticity of crystalline rock "B," another measures sonic velocities of crystalline rock "C," and so on.

All of the specialists with whom I've talked who are conducting these studies (see "Acknowledgments" section) agree that we are long overdue in getting the bits and pieces pulled together into integrated cooperative programs. They further are unanimous in agreement that field and laboratory studies need to be wed by moving the laboratory into the field to conduct in situ studies.[17] This would permit the study of large masses of rock which are coupled with other rock masses and which are affected by seismic vibrations and other natural processes.

It seems to us to be essential that we make all the specialized tests on the same rock taken from outcrops or drill holes in rock masses whose local and regional terrane settings are well known. Evaluation of the rock sample and of the terrane mass must be made in context with

[17]This recommendation was also made by those of us who participated in the LBL Workshop (LBL, 1979, p. 126).

one another. All the different tests performed should be made and interpreted in context with one another--each would provide new insights of understanding of the interpretation of the other. The results would surely be synergistic.

The Swedish-American cooperative study at the Stripa Mine, referred to earlier in this report, is a good example of an approach to such an integrated study. However, even that study is primarily one of fracture hydrology and is not yet integrated with studies such as regional and local petrology and in situ stress, for example. Plans are being made to broaden the study to include such aspects.

The other topics of recommended research would most effectively be conducted as part of these integrated in situ programs.

Depth Relations of Fractures and Permeability

Throughout this report I have tried to point out that virtually all the reports and current research on crystalline rocks are pervaded by the untested assumption that the flow of water will be by fractures rather than by matrix permeability. The lines of evidence for questioning the validity of this assumption were stated in the second section on hydrology, p. 39 above, and will not be restated here.

It seems to me that a first order of business is to test this assumption by determining the permeability of several different crystalline rocks in several different tectonic settings (table 4). If the flow at repository depths is indeed dominated by fractures we would know with certainty, and learn to live with the great complexities involved in modeling such a system. On the other hand, if fracture flow could be shown not to exist in that environment, the modeling is orders of magnitude more simple and there are far fewer uncertainties to live with.

Inasmuch as the outcome of these tests so drastically dictates the nature and direction of subsequent research, it seems imperative to start them at once.

Isotope Studies of Permeability

Long residence time (age) of water deep in crystalline rock terranes has long been used as an argument for very low permeability in such rocks. However, the age of the water only tells us how long it took to get there--not how long it will take to get from there to the nearest discharge point. That, of course, is the critical rate. Additional determinations of age of water at or near the nearest discharge point would provide the needed data.

It has been pointed out that this water from deep within some crystalline rock masses is a mixture of water of two ages: one is the older water trapped in the pores and other "dead-ends" of the circulating system; the other is younger water that is actively moving through the rock. Techniques have been developed for discriminating these two ages of water, so that correct rates can be calculated.

In addition to the above well-established method of applying isotope analyses, a fairly new technique has recently been used. This is the method of U-equilibrium/disequilibrium described above (p. 42) and first mentioned for waste disposal studies by Peterman.[18] This highly promising technique seems worthy of continued research.

A substantial amount of data exists on U-Pb systems in metavolcanic and granitic rocks of different ages and tectonic settings (Z. E. Peterman, written commun., 1978). Of special significance are the following:

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[18] "Isotopic and geochronologic studies of the Wyoming Age Province", in Smedes, 1978, p. 104-105.

1. Uranium loss is common in surface exposures.

2. Uranium loss is common at considerable depths in highly tectonized terrane. Crystalline rocks from such areas have had their physical and isotopic integrity compromised by fracturing that allowed deep movement of fluids. Clearly these areas should be avoided in preference to crystalline rock in stable areas.

3. Some crystalline rock masses in stable regions exhibit "closed-system" behavior by the equilibrium assemblage of their contained radionuclides--for extremely long periods of geologic time.

4. Volcanic rocks are highly susceptible to nuclide migration during early stages of low-temperature alteration and through prograding metamorphism to greenschist facies. The data suggest that metavolcanic rocks are more suitable as containment media than are pristine and altered volcanic rocks.

Isotope Studies of Thermal and Tectonic Stability

There are several isotopic systems that provide useful "clocks," each of which is set to start ticking as the host minerals in the rock cool below different temperatures. The "clocks" can be reset by heating to above that temperature. As described above ("Tectonism," p. 33-34) these isotope methods have been used to determine the location, time, and magnitude of a major tectonic event in Wyoming (Peterman and Hildreth, 1978).

Microfractures

Microfractures reflect the present and past stresses which have affected the rock masses. These fractures strongly influence important attributes such as matrix permeability, rock strength, chemical reactions, and geophysical properties, as discussed above (p. 33-34)

These fractures, and related strain phenomena such as deformation lamellae and strain shadows are records, in the rocks themselves, of how the rock behaved in the presence of stress. Presumably, these effects would first appear, and then become more pronounced and widespread as a fault is approached. Tests of this relationship are desirable in that the results hold out hope of telling us how far away from a fault is "far enough," and of helping detect a fault which is not detectable by conventional means.

The presence, nature, and abundance of microfractures may correlate with "equilibrium" versus "disequilibrium" rocks as described above for isotope studies--they may afford the avenues for fluids which have moved through the "disequilibrium" rocks.

Depending upon the nature and abundance of microfractures in rocks, permeability apparently may be changed in quite different ways during the heating of the rocks by the waste. This conclusion is founded on the following examples from laboratory studies of granitic rocks: Heating the Westerly Granite at 100°C reduced the matrix permeability by a factor of about 50 in only 10 days (Summers and others, 1978). Water moving through the intergranular voids and microfractures caused clay alteration of the surfaces of feldspars which resulted in plugging of those channelways. Incidentally, not only was the permeability greatly and rapidly reduced, but it was done so by the formation of minerals which also are highly sorptive. Similar experiments by Potter (1978) on the Westerly Granite and a quartz monzonite from the Los Alamos region of New Mexico showed differences in nature of microfractures, which he interprets as due to the respective temperature and pressure environments in which the two rocks became equilibrated in nature. The rocks from the Los Alamos area had existed at moderately high temperatures and pressures for some time inasmuch as they were from core at the geothermal test hole at a well depth of approximately 9,000 feet where the present rock temperature is about 200°C.

Surrogate Data

Some properties of rock masses may not be directly determined by any feasible means. In those cases, it is important to consider whether there might be some other attribute present which (a) has high covariance with the desired property, and (b) is already known or can readily be determined. These readily determined properties provide an efficient means of getting a reconnaissance of first-approximation understanding of the likely behavior or occurrence of the primary data sought. For this reason they can then be used as a surrogate for the original property desired. This will be of greatest concern and use in the screening process to select sites from among larger regions.

Examples have been given above on the relation of topography to the configuration of the water table (this report, p.33); others will need to be developed. Some of the required data on homogeneity of the large masses may be approximated, using the method of surrogate data just described. For example, interpretation of images from aircraft and spacecraft can readily provide much useful data at very low cost. The nature of inhomogeneities in vigor of vegetation may be detected in color infrared photos or by scanner data of the same (near infrared) spectral region. The importance of this is that the vigor may be demonstrated to be a function of either shallowness of the water table or of tensional joint sets which retain more moisture than the unfractured rock. Inhomogeneity of spatial frequency of joints can be determined in the latter case. Because of the different values of thermal inertia for different bedrock types and different degrees of depths of weathering, predawn thermal infrared images may help in mapping inhomogeneities.

Application of these remote-sensing and other techniques, such as aeromagnetic surveys, will help define the boundaries of the structural domains which are such an essential element of the geometry of a region. Aeromagnetic and other rapid geophysical techniques can provide data on lateral and vertical inhomogeneities in rock type, structure, and water content.

Other examples of surrogate data are strain in rocks and minerals as clues to tectonism, and residence time of water on the state of equilibrium of natural isotope systems as measures of the in situ permeability of large terrane masses.

Microfractures with certain characteristics and that are anomalous from the regional baseline may prove to be surrogates for whether a site is "far enough" away from a fault (this report, p.18). Lineaments compiled from satellite images may prove to be good surrogate indicators of the differences in relative density of joints and microfractures from one region to another.

Geophysical methods such as seismic velocity may, when calibrated against solid rock, provide some measure of the proportion of voids between two widely separated shallow drill holes in granite. Although the data would not indicate the range in apertures or degree of connectivity of the voids, they would give a measure of potential waterways in the rock. Electrical methods will indicate presence or absence of water but will not give information on the dynamic state--whether the water is trapped or moving through the rock. Each method serves as a surrogate to obtain parts of the answer to critical questions.

It is recommended that attention be given to develop and test more of these surrogates.

Geophysics and Rock Mechanics

Because we must be able to determine and characterize the nature of a rock mass at depth with only a few drill holes, geophysical methods are vital. Research underway should continue to be supported to test and develop improved capabilities of these techniques, and to couple or calibrate one with another.

In the section on "Stability" (this report, p. 34), crystalline rocks were stated to have superior strength. On the basis of laboratory tests of rock specimens, this basic assumption is valid. However, it remains to be determined what the strengths of the rock masses are.

The mechanical properties of the rock phases must be determined for they give the rock its geophysical response and they provide clues to present and past stress history of the rock. Further research is needed to learn more about how to interpret the stresses locked into the rocks (this report, p.36) and to be able to predict, by modeling, the long-term mechanical behavior of the rock. This becomes all the more important when we consider perturbations caused by excavations and by heat from the waste (this report, p. 40). Research on the nature and effect of in situ stresses is needed in order that we may assess whether they reduce or enhance the stability of the rock mass at a given site. The effect of water on the subsequent behaviors of the rocks is not well known but probably is important (Lee and others, 1979).

Refinement of electrical methods holds promise of determining more precisely the presence or absence of water at various depths.

Natural Examples

One of the threads running throughout this report is that of looking for answers in the rocks themselves. In terms of seismic risk to the repository (apart from the short-lived structures for handling the waste), I suggested, above, that we look at the rocks. Do they have in situ stress, microfractures, or strain features in the component minerals that are anomalous? (This report, p. 18, 33, 34.) Just because a site is in a high seismic-vibration zone (fig. 10) doesn't mean that we should reject the site a priori. The rocks at that site have been tested time and again--if they have passed the test, why reject them? To study the effects on the rock of known seismic events is one of the ways to learn about the future behavior of the rock mass from an example in nature.

Many of these natural examples will provide a "worst case." It is important to know that even if the worst that can happen does happen, the rocks and site remain suitable.

Heater tests are being conducted in Sweden (Witherspoon and Degerman, 1978) and in the U.S. (Ramspott, 1976). The heaters are to simulate the heat from the canisters of waste. Instruments measure the rate, amount, and nature of thermal expansion, crack generation, and related properties. A shortcoming of the tests is the short time they are conducted compared to the nearly 100 years the rocks in the repository will actually be heated. Here, again, we may be able to obtain useful data from natural phenomena: In many places, dikes cut crystalline rocks (rock salt and shale as well!). In some it can be determined that presently exposed parts were at depths of only 1,000 m or so beneath the surface--analogous to repository depths. These dikes were conduits through which lava moved to the surface, to form lava flows; some were conduits repeatedly and for thousands of years. Not only was the temperature far greater than that postulated from waste canisters, the rocks were cycled through many episodes of heating and cooling--certainly a thermal "worst case." Yet the host rock appears mechanically and chemically sound. Clearly, these localities afford an unrivalled opportunity to study the mechanical, chemical, isotopic, and hydrologic effects of heat.

To learn more about hazards of faulting for example, we should look to natural occurrences where faults have cut and displaced thick sections of unconsolidated rubble. The rubble would be somewhat analogous to the backfill in the chambers. Did the fault cause great physical disruption nearby? Did it cut across or was it deflected around the large clasts in the rubble? This will give ideas of whether or not that kind of fault would cut through a waste canister, crush it, or be deflected around it and cause no harm to the canister. To ensure that deflection will occur, it may be necessary to reconsider the nature and behavior of the packing material.

To learn more about volcanic hazards to the repository, we should look for places where dikes cut unconcolidated rubble analogous to the backfill of the repository. What were the physical and chemical effects and how far did they extend away from the dike?

Examples of both faults and dikes cutting rubble like that described above are known from many accessible areas. They could readily be studied and their impacts on a repository bracketed within some range.

Many aspects of chemical reactions with the waste can be learned from host rocks of uranium ore and from the natural prehistoric "reactors" such as that at Oklo in Gabon in west-central Africa (Nevilly and others, 1972).

These examples are intended to serve as an indication of the kinds of phenomena we should look for in nature, to give us clues to the possible range in magnitude of effects that may take place in the repository. I think it's exciting to contemplate conducting studies of such features with a waste-disposal application in mind. I suspect these studies will lead to our playing-down the hazardous effects of many events that presently make us fearful. The results of such studies will play important roles in the establishment of criteria or guidelines for actual repository siting.

CONCLUSIONS

The rationale presented for geologic isolation includes an elaboration or explanation of why certain criteria have been ascribed, and what the consequences (if any) would be if the criterion should fail to be met. In part, this amounted to asking the question "so what?"--and attempting to answer that question.

A number of compelling lines of evidence very strongly suggest that at least some crystalline rocks in some areas are not fractured at repository depths, therefore the widespread premise that the problem will be fracture hydrology needs to be tested as a first priority of research. The outcome should guide forthcoming programs--it may well result in a drastic and prompt realinement of research priorities.

New applications of isotope geochemistry are described which can provide important new data on the bulk permeability of large masses of rock and on long-term stability. A study of microfractures; surrogate data; and natural examples of such topics as heater "experiment," faulting, and volcanism are recommended in addition to those fields of study already being pursued. It is urged that all of the studies be integrated into a cohesive program making optimum use of in situ study areas to be developed.

Crystalline rocks have a high potential as suitable sites for repositories of nuclear waste. Although they share many problems with most other rock types including salt, shale, and lava, they are superior in many ways. Because of their abundance, they offer far greater potentially suitable sites. They are widespread in large and deepseated commonly homogeneous masses exposed at the surface and beneath all the younger sedimentary rock cover which in many places is thin. Their great physical strength has permitted underground excavations to remain intact without support for centuries. At depth, water content is low or absent, and permeability is very low. Some of these rock masses have remained thermally and tectonically stable for more than 1 b.y.

Large bodies of crystalline rocks in many regions have high likelihood of providing repositories which: (1) are large enough to handle a variety of waste forms, (2) are stable and strong enough to protect the repository and to permit a ready retrieval long after emplacement of the waste, and (3) a vertical extent far more than sufficient to allow for a repository at depths below the zone of fracture and below possible levels of exhumation by erosion. For purposes of repository siting, many of these crystalline rock masses can be considered as bottomless and the larger ones--batholiths and high-grade metamorphic rocks of the craton--certainly will not have an aquifer <u>beneath</u> them as is possible with sedimentary rocks and volcanic rocks.

Heat produced by the waste seems to pose the most serious geological problems to isolation--in any rock medium. This heat production diminishes with time and is of greatest concern during the early life of the waste. For these reasons it may be desirable to store the waste for several decades.

A rationale is presented for site selection which allows for the various degrees of uncertainty in the data. Because there are no absolute guarantees in the selection or verification of sites, modeling will provide a range of alternatives bracketed by a "best case" and a "worst case".

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