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State of Geological Knowledge Regarding Potential Transport of High-Level Radioactive Waste From Deep Continental Repositories

Report of An Ad Hoc Panel of Earth Scientists

EPA

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FOREWORD

A major Federal effort is underway to develop methods of disposal of high-level radioactive waste. An important element of this program, scheduled for early completion, is the development and promulgation by the Environmental Protection Agency (EPA) of environmental standards for such materials.

In conjunction with its efforts to develop these standards, EPA is using state-of-the-art techniques to estimate the expected and potential environmental impacts from potential waste repositories, including repositories in deep geologic formations. It recognizes, however, that there may be significant uncertainties and controversy regarding knowledge of rock properties, hydrogeology, and other factors, especially as they relate to the ability to provide long-term containment of radioactive wastes.

Therefore, in order to assure the protection of public health, EPA believed that an expert panel was needed to evaluate objectively the adequacy of basic knowledge in the pertinent earth sciences for reliably estimating environmental impacts.

In March 1977, the Environmental Protection Agency contracted with Arthur D. Little, Inc., Cambridge, Massachusetts for technical studies of high-level radioactive waste disposal using deep geological repositories. Directive of Work No. One under this contract, issued in June 1977, required that the contractor, in conjunction with the EPA Project Officer, select the Ad Hoc Panel of Earth Scientists comprised of nationally recognized experts in the fields of geology, geochemistry, geohydrology, rock mechanics and other applicable disciplines in the earth sciences. The Panel's basic charge was to perform an independent evaluation of the adequacy of the state of knowledge in the earth sciences for reliably estimating the environmental impacts to be expected from the disposal of radioactive waste in deep geologic formations, to provide guidance to EPA regarding the uncertainties inherent in estimates based upon such knowledge. This report was prepared by the Panel in response to its charge.

The Panel conducted its work and formed its conclusions independently of Arthur D. Little, Inc., EPA, or any other agency. EPA and its contractor provided only administrative services and such procedural assistance as the Panel requested.

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PREFACE

In August of 1977, a panel of geologists, geochemists, and geophysicists was brought together by Arthur D. Little, Inc., under assignment by the Environmental Protection Agency (EPA) to evaluate the state of knowledge in the earth sciences relevant to environmental aspects of the disposal of high-level radioactive wastes (HLW), by deep burial on the continents. This report presents the results of the panel's work in 1977.

This report contains our evaluation, based on the available written reports of individuals and research groups in government, industry, and the universities; as well as meetings of the panel, subgroups of it, or individual members with several individuals currently active in this field. We have met as a group with members of the Arthur D. Little Staff and the Office of Waste Isolation (OWI) at Oak Ridge.

We have tried to find out the nature of the pertinent efforts at other government agencies and their contractors, including groups of the Department of Energy (DOE), formerly the Energy Research and Development Agency (ERDA) and the Nuclear Regulatory Commission (NRC), Arthur D. Little, Battelle Northwest Laboratories (BNWL), the United States Geological Survey (USGS), Sandia Laboratories, Los Alamos Scientific Laboratory, and Lawrence Berkeley and Lawrence Livermore Laboratories (LBL and LLL). We do not claim to have made a detailed and comprehensive survey of all of this work; neither time nor manpower allowed that.

We have attempted to assess the research that has been or is being done, or that is planned, so as to identify what needs most to be known in the earth sciences in order to permit reliable prediction of the behavior of HLW following deep burial. We do not make judgments on the merit of any specific research effort of any organization or individual. Our aim is simply to find out what is known and what is not.

We have taken as our charge an assessment of the state of the art of the geological sciences that relate to the disposal of radioactive wastes at some depth under the land surface. How well do we know the physical and chemical characteristics of the rock materials at depths comparable to those envisioned for waste disposal? How reliably can we calculate such diverse quantities as rates of chemical reactions around waste containers and hydrologic flow rates in low-permeability rocks? Can we predict the likelihood of changes in the current geologic regime that might affect the storage site in the future?

We include in our charge judgement of the confidence with which we can predict the extent of transport of radioactive materials and how this relates to certain kinds of geologic formations in various tectonic and surface environmental settings, but we do not assess the merits of any particular site. We consider three phases of the problem:

(1) what we can do now,

(2) what we can find out within the short term--a year or two--that will allow us to do much better, and

(3) what we can determine only after several years of well-planned, careful research.

Implicit are the questions: do we know how to formulate the right specific questions and can we expect to obtain answers of sufficient accuracy to suffice for our needs?

Increasingly earth scientists are being called upon to predict future geologic phenomena specifically. Earthquake prediction is relatively advanced because of the important research of the past few years; prediction of climatic change is an actively researched subject. Short-term prediction of volcanic eruptions is possible now. On a less spectacular level, hydrologists can predict with fair accuracy the behavior of ground water flow under various pumping regimes. Yet most of these predictions are valid over time scales of days, or a few tens of years at most. In contrast, our ability to predict in any but the most general way over times of thousands of years is poor, yet this is the interval over which we must forecast if an underground HLW repository is to be safe for future generations.

Our study is intended to inform the EPA of the nature of the advice that it is getting and can expect to get from competent earth scientists who are knowledgeable about the various aspects of, and current developments in, the background science of the problem. From such sources the EPA should expect assessments and predictions that are solidly based upon current knowledge, not hypothesis and extrapolation from inadequate or inapplicable field or laboratory data. Above all it should be remembered that the Earth--or any small part of it--is an extraordinarily complex and heterogeneous assemblage of materials, constantly subject to slowly acting forces. Attempts to model its behavior in this case must rely not simply on the best data that are readily available but on <u>sufficiently good</u> data that are truly pertinent and on a consideration of all of the important factors that may affect the outcome. In any case, we must know the reliability of any estimates before we can use them as a basis for practical decisions.

In assessing the possibility of loss of integrity of a disposal site, we have considered that total containment is desirable. Realistically, however, some loss of radioactive material, albeit small, appears likely. We have addressed the question of estimating the amount of contamination to the biosphere. It is worth noting that estimates of (and regulations concerning) maximum permissible levels of radioactivity in different phases of the biosphere have been lowered over the years since World War II, and we must assume that this trend will continue into the next few centuries.

In preparing this report we have been assisted by the many individuals who have talked with us, sent us reports of research in progress, and informed us of where work is going on. We have consistently found a high degree of cooperation, which has made this task easier, and for which we are grateful.

We acknowledge the important contribution of Arthur D. Little, Inc., in bringing us together and informing us of their work, facilitating our task, and seeing our report through publication and submission. We alone, however, are responsible for the contents and conclusions of this report.

PART I: INTRODUCTION AND STATEMENT OF THE PROBLEM

The impetus for addressing the questions we seek to answer is the necessity for long-term storage or disposal of various kinds of long-lived radioactive wastes that already have been generated by nuclear processing plants and reactors and that will be produced by current and future nuclear power reactors. We consider high-level wastes of two categories:

(1) those generated by the reprocessing of spent fuel rods, and

(2) the unprocessed spent fuel rods themselves.

Wastes of both kinds must be stored in such a manner that leakage from the deeply buried repository to the biosphere will be inconsequential to public health over the times during which the stored materials remain sufficiently radioactive to be hazardous. Thus we consider a maximum time scale of hundreds of thousands (10^5) to a few million (10^6) years, but pay special attention to the dangers of leakage over shorter terms up to a thousand years, when the levels of radioactivity are highest.

Unlike ordinary engineering problems, there is no experience with long-term, sealed underground storage of such materials, and thus no foundation of empirical knowledge upon which to build. Almost all of our experience with underground openings relates to technologies designed for removal and extraction, such as mining and pumping for water, oil, or gas. There is some limited knowledge from the underground storage of gas, oil, and water. However, small leaks of these materials would not be significant and, therefore, are not studied.

The engineering design of underground openings such as those envisioned under various HLW storage plans is like nothing ever developed previously. This basic difference stems mainly from the addition of radioactive heat to the normal geothermal temperatures at the relevant depths on the order of 500 m.

We assume that a safe underground repository requires a volume of rock in a stable geologic environment. We envision storage in an area that is subject neither to frequent, high-energy earthquakes nor to volcanic eruptions. Variations in the hydrologic regime due to climatic variations of rainfall and evapo-transpiration must not jeopardize the safety of the biosphere from HLW contamination. Above all, we assume that a rock environment is required that is sealable and has a minimal permeability for fluids and the radionuclides that might become dissolved in them.

The rocks that now seem to be most suitable are salt, shale, basalt, and certain rocks of the granitic clan, but anhydrite and some impermeable tuffs may be worth considering. Other common rock types, owing to their permeability or chemical reactivity, are not worth serious investigation at this time.

A central consideration for a great many questions is the type of waste to be stored. Until recently storage schemes have been predicated on the reprocessing of spent fuel to HLW and its subsequent combination in concentrated form to produce a calcine, ceramic, or glass cylinder encased in a metal canister. Small in volume, these canisters develop high temperatures in the first few years, when short-lived radioactivity is at its highest level. For the first 10 years or so the material would have to be stored above ground in order to allow rapid heat loss. After this time, during the initial period of underground storage, the canisters may reach temperatures of 300°C or more, depending on the thermal conductivity of the surrounding rock. Nevertheless, these canisters enclose the HLW in a form that is designed to be far more resistant to corrosion and leaching by formation waters than unprotected spent fuel rods would be.

Storage of spent fuel rods presents fewer heat problems: the radioactive materials are in less concentrated form and would not be expected to reach temperatures greater than 100°C. However, the rate of corrosion of the fuel rods would be much greater, and great reliance would have to be placed on the impermeability of the surrounding rock to contain the HLW. Although relatively little work has been done on the feasibility of storing spent fuel rods, current federal policy favors this option.

Reprocessed HLW or unprocessed spent fuel rods both contain a mixture of short- and long-lived radioactive elements of two kinds, in addition to the unconsumed ^{238}U and ^{235}U. These are the fission products such as ^{137}Cs and ^{90}Sr, and the transuranic (TRU) elements such as Pu, Np, Am, and Cm. Fission products and transuranics have different chemistries, as well as a range of radioactive half-lives, so that we must consider a variety of geochemical reactions with host rocks over time scales ranging from a hundred years to a million years.

We know all of the decay constants for these materials sufficiently accurately, but there is a wide disparity in our knowledge of their chemistry and geochemistry. In particular we know little about how these materials react with real rocks and minerals at the temperatures and pressures expected in the subsurface. For example, the few laboratory data on the adsorption of Pu on "desert soil" or even "montmorillonite" at 25°C and atmospheric pressure from relatively dilute solutions are inadequate for predicting the sorption of Pu on a rock at a temperature of 200°C and pressure of 150 bars. Such a rock may contain an assemblage of minerals that includes partially devitrified volcanic glass; several zeolite minerals such as analcime, mordenite, and clinoptilolite; plagioclase feldspars; and several varieties of smectite minerals, each with its own variable chemical composition and different ion-exchange characteristics. The rock may contain highly concentrated brines with a mixture of dissolved salts that may radically alter cation exchange reactions.

The reliability of our estimates of the geologic future of a repository formation falls off dramatically with time because of the long time scales of many geologic processes and the unpredictability of many geologic events. Beyond a few hundred years our estimates become rather uncertain; beyond 10 thousand years they become marginally reliable; and for times greater than a million years they become so poor that they become little better than guesses. Of course the reliability also depends on where the repository is with respect to the tectonic framework of the continent. We can be much more confident of the stability of old granites on a Precambrian shield than of young basalts near a tectonically active continental margin such as the Pacific coastal regions of the U.S.

Finally we must confront the issue of retrievability of the HLW over a specified time period. Because high-grade uranium ore resources are limited, it may be desirable at some future time to recover unprocessed fuel rods and reprocess them for what may have become much needed Pu and U. Indeed, it would appear that a breach of the repository in order to mine the U and Pu could be a serious problem for the future.

The geological site selection criteria for and engineering design of repositories will be strongly affected if retrievability is deemed to be desirable. It is unlikely, for example, that spent fuel rods could be safely recovered from a repository in salt more than a few tens of years after emplacement and backfilling, for by then the salt would have completely sealed the openings. Storage in granite or shale might be more desirable if long-term mechanical stability is required. As yet there is no firm policy. We must consider the state of knowledge concerning the reopening of underground workings in the rock types proposed for storage and how such reopenings--or maintenance of a tightly sealable, open shaft--affect the choice of storage repositories.

Here again we are faced with lack of experience, for in ordinary mining operations, openings are usually abandoned after working, with no thought of returning. Though there has been some reworking of mines in a few places, these are highly hazardous because of the danger of roof-falls in a deteriorated mine. It is well known that keeping any underground mine open and clean requires constant maintenance and checking of rooms and entries. The deeper the mine the greater the danger of rock bursts and floor heaving, the more so because accumulated strain in surrounding rock may build up over a long period of time and then suddenly give way by failure.

Retrieval may only be feasible so long as an active crew is kept at the repository site, perhaps then for only a relatively short number of years, 5 to 10, while the repository is being filled. We assume that constant underground human surveillance for significantly longer periods of time is unlikely.

In the sections that follow we discuss specific details of the integrity of the storage assembly itself, the nature of the various rocks in relation to their suitability for storage, the transport of radionuclides through rock barriers, the hydrologic regimes, and the probability of disruptive geological events.

PART II: THE CONTENTS AND PROPERTIES OF THE CANISTER

Most planning to date for possible designs of HLW storage and disposal systems deep underground has included several stages of containment in case parts of the system were breached. These stages usually include: the resistance of the waste, in whatever form, to leaching and transport; the resistance of the metal canister to corrosion or other loss processes; possible special materials placed immediately around the canister; the geological formation into which the repository is to be placed; and the nearby geological formations surrounding the host formation itself. These containment stages have permitted computation of a variety of time delays prior to possible release of the HLW to the biosphere. The various model computations utilized have differed in the nature of the materials employed and their geometries.

The nature of the HLW-containing "vessel" cannot be defined clearly because no firm decisions have been made concerning a number of parameters to be listed below. By "vessel" is meant the canister and its contents, plus any packing placed immediately around the canister on out to the undisturbed rock wall. The parameters that have not been defined include:

- The composition of the canister waste contents. That is, the relative proportions of fission products (^{238}U + ^{235}U) and TRU elements are not defined because it is not known if the materials will have been reprocessed, or even if spent fuel rods will be placed in the canisters directly.

- The composition and phases of the canister contents. This includes the inert (radioactively) materials used as "binders." Glasses, calcines, and ceramics have all been suggested as possible candidate materials into which the HLW could be incorporated.

- The "mix" and concentration of the HLW in the canister. This affects the heat production rate and its variation with time.

- The nature of the canisters. It is generally assumed that the canisters will have approximately a 1-ft inside diameter and an approximate 8-ft length. It is not clear what material(s) will be used to make the canisters. Steel, stainless steel, and molybdenum have been named as candidates, but this is clearly not an exclusive list. Wall thicknesses appear to have been considered for purposes of transport of the contents to the repository only.

- The nature of the packing around the canisters. This has included as candidates: metal sleeve, useful if recovery at a later date is desired; zeolites or clays with high ion-exchange capacity; crushed rock of the type in which the repository is placed; this same rock or other material cemented together; some combination of these.

It should be clear that much of the uncertainty concerning the basic characteristics of the repository resides in two areas: policy decisions have not yet been made and accepted generally, concerning whether or not the materials will have been reprocessed, and whether or not to provide for retrievability of the HLW for time scales of decades. The consequences of these policy decisions concerning the mode of HLW disposal might, in fact, eventually result in revision of the choices made with respect to the form of the waste, storage, rock type, and site.

II.1 THE INTEGRITY OF THE HLW AND ITS MATRIX

Several materials have been proposed for mixing with the HLW so as to provide a solid composite that would resist leaching or other loss of the HLW in the event of canister breaching. Included are calcines, ceramics, and glasses. The possibility that the leaching solutions would be acid has argued against the use of calcines, since they are not very resistant to such attack.

The use of ceramics may be viable, but not enough work has been done to demonstrate that. In view of some of the difficulties with glasses to be discussed shortly, ceramics might well be worth more intensive study. They have the advantage that they are already crystallized so that devitrification is not a problem. Questions concerning their stability and resistance to leaching under the local pressure and temperature conditions of the solutions that are likely to exist need to be explored.

Various glasses have been suggested as suitable products to be placed into the canisters. The ability to make a homogeneous phase that will fully occupy the canister shape, the good compressive strength, and the moderate resistance to solution, all are positive arguments for the use of glass. There are two phenomena that can generate serious problems in the use of glasses, however. These are that glasses are not stable, but will tend to devitrify; and that it is possible that solutions of high ionic strength will leach the glass at the ambient temperatures around the canister.

Two aspects affecting the possible devitrification of glasses have not been adequately investigated. The first is the high radiation flux from alpha particles. These can create considerably more recoils and damage than beta particles and gamma rays. It is primarily the latter that have been used in tests for devitrification. With the new possibility that unprocessed fuel rods will be used, or that the HLW might be made into a glass without prior separation of the U and Pu, the dose of alpha particles will increase markedly. The devitrification will also be enhanced by the presence of water, particularly high ionic strength solutions, at somewhat elevated temperatures. We are unaware of any tests conducted on any of the proposed types of glasses that show the effects of high dosages of alpha particles imposed on glass during immersion, in likely corrosive solutions, at the various temperatures from 300°C on down. It would not be at all surprising to find that the integrity of the glass was lost over time scales of a decade, instead of the millenia that are now computed on the basis of the results of dry tests with gamma and beta radiation.

The consequences of devitrification are the formation of one or more crystalline phases. Such processes commonly result in the formation of materials with simpler chemical compositions than the glass. The new phase excludes impurities. If the impurities include the class of nuclides that are the fission products or TRU's, then these will end up in inter-granular boundary areas. Leaching of these would then be relatively easy, and the bulk of the original glass need not even go into solution, but could remain as relatively non-radioactive crystals.

The other area that requires demonstration is the leaching of glasses, even if no devitrification is assumed to occur. Experiments need to be conducted with solutions at temperatures as high as those that may occur in the canister, clearly higher than 300°C in some cases and possibly in excess of 500°C. These solutions should include the likely ones for the proposed setting: such as concentrated brines, including the variety of bitterns that exist as fluid inclusions in some rocks.

At this point, the Panel believes that there is no evidence that incorporation into a glass will ensure resistance to significant leaching over time scales of a decade. We wish to make clear that this is an area in which experiments can be done. If carefully controlled, such studies should be able to answer the question reasonably well.

In the event that containment by the glass was necessarily a short-term phenomenon, the primary defense against migration of radionuclides to the biosphere would clearly have to reside in the other containment stages referred to at the beginning of this section. We assume that it is of little importance whether the glass releases some radioactive waste in times of a decade or hour, since the effect would be essentially instantaneous compared with the time scales of interest for HLW. We shall assume, therefore, that the glass presents no significant barrier to transport by leaching solutions.

If the spent fuel rods are placed directly into the canisters, or are not changed chemically (that is, they may be crushed and pelletized), we know of no data concerning the ease with which such materials will be leached. It would be expected that the material is so far out of chemical equilibrium with the hot solutions that can reach it, however, that a significant amount of solution would occur. We see no safe alternative at this point but to assume instantaneous access to leaching solutions. The limiting constraint we see here, as with the glasses, is the degree to which the individual ions are soluble, either as those ions or as complexes.

In dealing with questions of devitrification kinetics, solution of the various compounds and glasses, or solution of the spent fuel rod materials themselves, some items should be noted. It is the repeated experience of those of us who work in this area:

- that rates measured in dry systems often are orders of magnitude slower than those measured in wet systems;

- that rates measured with pure water or dilute solutions are often far slower than those in concentrated solutions, particularly if the latter are at high or low pH; and

- that complexing of ions (by making chloride complexes, as an example) may permit considerably higher concentrations of the cation in the solution.

Transport of ions in such cases would clearly be faster for the same volume of solution.

The use of some data in this area in the mathematical models that have been constructed for HLW is justified as the only information then available. However, we should not lose sight of the major discrepancies possible between available data and those that are needed to bear directly on what the models are trying to determine.

Until it is demonstrated otherwise, we conclude tentatively that a loss of integrity of the HLW matrix in a repository would result within a very short time of the emplacement. This short time could well be less than a decade. In view of the need to maintain isolation for time scales of centuries to one million years, it appears safest to consider the materials in the canister primarily from the aspect of what is being dissolved and transported rather than as barriers of any consequence.

Some comments are in order concerning the nature of the solutions that might attack the canisters and their contents. It is clear that the rock type will affect to some extent the nature of the solutions.

A frequently discussed candidate lithology for a repository is salt. Observation in salt mines has shown that chambers cut into some salt deposits remain dry indefinitely, suggesting the long-term safety from water that is desired for HLW. Closer inspection of salt, however, reveals that the crystals do contain significant amounts of water as fluid inclusions and along intergranular boundaries. Work done by Roedder and by Stewart (to be discussed in Part IV) suggests that a potential hazard exists here. The fluid inclusions in the salt decrepitate (burst on heating) at comparatively low temperatures, which means that they are reasonably certain to do so in the vicinity of the canister as the temperature rises following emplacement. Decrepitation is quite likely to occur at temperatures in the general vicinity of 150°C. If we assume that the wall temperature of the canister will reach 300°C, a significant amount of water might be available. This is most likely in bedded salts where water may be in excess of 1% of the rock. It becomes imperative to determine if similar amounts of water exist in the salt of salt domes.

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The process of migration of water up thermal gradients in salt has been described numerous times. It is cited here to make the point that the canister is likely to be bathed in water soon after emplacement. This water would, of course, be saturated with salt. At the temperatures encountered at the wall, the concentration is considerable (as will be discussed).

The availability of water in shale deposits is considerable. This is water normally tied up as water of hydration in the clays or as OH ions in the structures of the clays and micas. The high temperatures at the canister wall will suffice to release some of the water. Again, the water will contain a variety of salts in solution. These will derive from the cations in and on the clay particles. As a result, the composition will differ from that of an evaporite unit in which the salt unit itself will tend to dominate the composition. If the salt is largely halite, so will be the solution. In the case of the shale, the solution may derive from salts that were present during deposition and diagenesis, plus the contribution from the particular clays in the shale and their degree of diagenetic change.

The granite clan rocks and other igneous rocks will contribute water from two sources. The rock itself is slightly permeable, and there will have been long times available for the water to enter the rock as it would in any other permeable rock. Most crystalline rocks of this sort are not totally massive, but have joints and shear zones on numerous scales. These will again permit water to enter. In this connection, it should be noted that much of the water obtained in New England from "artesian" wells drilled in these crystalline rocks is actually from fissures in the rock. The rock itself is relatively impermeable if a particular specimen is tested, but the unit of rock is much more permeable owing to these fissures. In the event that HLW is stored or disposed of in such rocks, it is not clear what the maximum surface temperature of the canister would be. The thermal conductivity of both these rock types is less than that of salt by a factor of about 3, a difference suggesting some higher temperature unless different concentrations of the fission component of the HLW were used.

A source of water from minerals themselves would not be a problem in the "anhydrous" rocks such as basalt or the granulite facies rocks such as charnockites or anorthosites. These may contain quartz, feldspars, and pyroxenes, in various proportions. Basalts are common, but the granulite facies rocks are more rare.

Any of these crystalline rocks, when heated in the presence of water, will contribute ions to form a solution, the composition of which will depend on the rock composition, including its fluid inclusions.

II.2 THE INTEGRITY OF THE CANISTER

The canister into which the HLW would be placed is usually described as a cylinder of approximately 1-ft inside diameter and 8-10 ft in length. It is assumed that it would be made of some metal, that it would be sealed by welding, and that it would be able to withstand both the high temperatures that would result when the molten glass or other molten material was poured into it, and the stresses during transport to the burial site. The wall thickness is not known to us, but would presumably be on the order of 1/4 inch to perhaps 1 inch.

In all cases, a pure metal or an alloy appears to be the choice for the material. Suggestions include: steel, stainless steel, molybdenum, titanium, and copper. Each has different structural advantages and disadvantages, which are not part of our concern. The resistance to corrosion does, however, concern us. We know of no tests that have shown that any of the candidate metals will resist corrosion by the salt solutions that are likely to be at the canister surface for a significantly long time. Again we stress that the solutions will be at temperatures of approximately 300°C, will have a high ionic strength, may have very low pH, but probably will have very low starting concentrations of the metals of the canister. Under these circumstances, it is likely that the canister could be breached within time scales of a decade or less.

For this reason, we do not consider the canister to be a significant barrier to the solutions, at least for the time scales of centuries to a million years with which we are dealing. In passing, we might note that it is not essential that all components of the canister be resistant to leaching or attack. The optimum canister may prove to be one that is highly effective as a container and transport vessel and one that does not enhance attack by solutions on the canister contents by adding corrosive materials to the solution that will ultimately breach the canister.

II.3 THE INTEGRITY OF THE CANISTER SURROUNDINGS

According to our nomenclature, the immediate surroundings of the canister are part of the "vessel." That is, the vessel extends from the canister, through the packing around the canister, and out to the undisturbed rock. If the canister is to be retrievable, the packing would include a metal sleeve to permit easy withdrawal of the canister. Around this might be packed crushed rock similar to the host rock of the repository or some other material.

The metal sleeve would doubtless behave in a manner similar to the canister metal. It is assumed that the same metal would be used, since the use of dissimilar metals could well set up an electrolytic cell, with the consequent possibility of H_2 production and rapid corrosion of the metal wa[illegible]. The comments above for the canister apply to the sleeve material as well.

Any packing would have a porosity and permeability that are much greater than would the undisturbed rock. If grouting materials were used to cement the packing materials, the result would be a less porous and permeable packing, but the grouting would still be susceptible to attack by the solutions.

The variety of possible packing materials is infinite, and it remains to be shown that the selected material would enhance the resistance of the "vessel" to attack by solutions. The use of zeolites or other ion exchangers might help in the chemisorption of the HLW as it moved through the packing, thus delaying the migration of the radioactivity. The amount of such packing might not be sufficient to make a significant difference, however, because zeolites lose their water (and so their cation-exchange capacity) at temperatures well below 300°C. To be effective, the zeolite packing would have to be far enough from the canister to remain cool.

Based on the above considerations, we assume that the near-in stages of containment cannot be relied upon to effect any significant retardation of the release of the HLW. We include in the near-in stages all the components of what we call the "vessel," that is, the HLW in its matrix, the canister, any sleeve around the canister, and the packing around the canister or sleeve. By significant retardation, we mean for times longer than a decade.

PART III: MECHANICAL PROPERTIES OF ROCKS

The introduction of a repository into a geologic unit poses a number of mechanical requirements on the rock: the need for sufficient strength to allow safe excavation and occupancy until the repository has been sealed; mechanical integrity despite the subsequent high temperatures; low permeability; and absence of discontinuities like jointing or bedding; or a very small number of these. Knowledge of the mechanical properties for the various candidate lithologies varies considerably and some uncertainties remain for all rock types.

The Arthur D. Little report on "Assessment of Geologic Site-Selection Factors"(1) outlines problem areas fairly well, but it neither assesses nor criticizes the state of the art that is currently available to resolve these problems. Nor for that matter does any other recent document known to us except for the NAS (National Academy of Sciences) draft report on "Rock-Mechanics Limitations to Energy-Resource Recovery and Development," which should be published in early 1978.(2) We concur with the conclusion of its Subpanel on Nuclear-Waste Disposal that "present rock-mechanics technology is not sufficient to predict the full range of thermal effects on site containment caused by the emplacement of heat-generating radioactive waste. The Subpanel believes, however, that the improvements in technology needed to make such predictions within defined and acceptable bounds of accuracy can be acquired with the proper research and development effort."

The engineering design of mines and other underground works is largely empirical, but it is firmly based on many hundreds of years of practical experience. Except for rock bursts in deep mines in strong rock in which residual stresses can be very high (as in South Africa), accidents that threaten human life rarely occur these days because of failure of the rock itself. (The risks of flooding and explosion of accumulated gas remain all too high.)

The expectable configuration of a repository is essentially that of a room-and-pillar mine. In practice, excavation is designed for the maximum rate of extraction that is allowed by the short-term stability of the roof. In salt mines the rooms may close eventually, but gradually and non-catastrophically, long after they have been worked out and abandoned. In principle, long-term stability can be achieved by increasing support--reducing the open area relative to that of the pillars and, if necessary, providing lining and other reinforcement. Thus, the state of the art is such that a <u>mechanically</u> safe cavity could ordinarily be placed in virtually any rock, provided only that cost effectiveness be judged not by the value of the rock extracted but by the critical need to isolate high-level waste from the biosphere.

The facts are, however, that the design of an HLW underground repository is not ordinary, and there is no fund of previous experience because the wall rock will be subjected to temperatures greatly exceeding those due to the average geothermal gradient. The temperature will depend principally on the thermal conductivity of the rock and the thermal load imposed, which depends in turn on the time allowed for heat dissipation during previous surface storage and the size and distribution of canisters in the floor of the repository. Temperatures as high as 300°C should be expected in a highly conductive rock like salt. Heating to as much as 500°C might well occur in a relatively poor conductor like dry granite. Our knowledge of the mechanical properties of rocks under long-term loading in the laboratory at the relevant temperatures (300-500°C) and confining pressures (100-[illegible] bars) is fairly good for rock salt. It is practically nil for all other rock types.

Much experimental work has been done on the high-temperature creep of single crystals and artificial aggregates of salt, and work on natural samples from the Waste Isolation Pilot Plant site is progressing at RE/SPEC (a consulting firm in Rapid City, S.D.) and Sandia Laboratories. The laboratory data on flow laws are being incorporated into non-linear numerical models in order to predict the behavior of cavities in salt. Although extrapolation of laboratory data must still be tested and the codes must be validated by careful measurements in the field, our ability to predict the formation of salt should soon be adequate, given the current level of research effort throughout the world.

We are far indeed from the capability to predict, with sufficient accuracy, the behaviors of any other rocks because:

(1) data on mechanical properties under relevant conditions are lacking and

(2) most rocks cannot be treated as continua because discontinuities like jointing and bedding are nearly ubiquitous.

Because the need for underground isolation of HLW has been recognized for some 30 years, the long postponement of pertinent research on rock other than salt is unfortunate. The problems will not be solved quickly. The research is inherently time-consuming because the critical data are attainable only from creep tests of months-long duration. Furthermore, the required testing machines (to accommodate 10-cm specimens, at temperatures of 500°C, under pressure of 200 bars, and for a duration of several thousand hours) do not even exist. It may take a major research effort of 5 years to build the necessary laboratory facilities; to collect adequate data; to develop realistic, three-dimensional, non-linear, large deformation codes; and to validate predictions in the field.

In addition to the strength of rock, which relates to long-term mechanical stability, we must know a lot more than we do about thermo-elastic expansion, thermal conductivity, and permeability, particularly as they are affected by thermal cracking. These parameters relate not only to mechanical but also to hydrologic stability. A modest experimental effort is under way at Terra Tek, the U.S. Geological Survey, and a few universities and DOE laboratories. Several heater tests in the field are in progress or planned for the immediate future (Avery Island salt dome, RE/SPEC; granite, Stripa mine, Sweden, LBL;

granite, Climax stock, Nevada Test Site, LLL; basalt, Hanford, LBL; Conestauga shale, Oak Ridge National Laboratory, Sandia; Eleana shale, Nevada Test Site, Sandia; norite, Sudbury, Canadian Government). Valuable data on thermo-elastic deformation and permeability may be obtained in situ where they count. However, serious questions can be asked about the choice of sites and the scale of these tests, relative to the natural joint spacing. Often site selection seems to have been either geologically naive or directed politically rather than technically.

We feel compelled to emphasize, once again, the significantly different consequences of the alternatives of disposal and storage of HLW. Must the facility remain stable only for a decade while it is being filled? Can the cavity then be back-filled with rock and the access shafts permanently sealed? Must it stay open for several decades, perhaps indefinitely, so that spent fuel rods can be retrieved and ultimately reprocessed so as not to lose a valuable store of energy; so that mistakes could be corrected should isolation be incomplete; or so that canisters could be moved should the site fail altogether? A weak, ductile medium like salt should be mechanically ideal for permanent disposal but might be poor indeed for long-term storage with the option of retrievability. Salt will certainly flow readily at 200°C under expectable in situ stresses. Canisters will have to be isolated from the surrounding rock, and artificial support of the cavity would have to be provided.

Excavating a strong rock like granite is much more expensive, and because it is brittle and always jointed to some degree, it may not be as good a candidate for permanent disposal. On the other hand, granite, basalt, or other strong rocks seem preferable for storage, at least with regard to long-term mechanical stability.

In summary, we shall know enough in a year or two to compute the consequences of HLW disposal in dry, homogeneous, ductile salt that would be mechanically metastable for at least a decade, perhaps indefinitely if we are to pay the price for artificial support. On the other hand, we know very little indeed about either the long-term strengths of jointed, brittle rock masses at temperatures on the order of 300°C, or the effects of thermal cracking on the flow of fluids through them.

PART IV: CANDIDATE LITHOLOGIES

Several different rock types have been discussed as possible host lithologies for the HLW repositories. Important candidates are: salt, shale, granitic clan rocks, and basalt. Because of the undemonstrated security of the assemblages of materials in and immediately around the canisters, the containment by the rock that is the host of the repository becomes of paramount importance. This is probably the last stage of containment of the HLW prior to entry into circulating ground waters and contact with the biosphere.

We do not attempt to review the properties of the different lithologies. Rather, we focus on the physical and chemical properties that bear directly on the question of HLW transport.

The first category discussed is salt. This occurs in two ways in nature, as bedded salt deposits in a sedimentary sequence, and as salt domes. Because their characteristics are quite different, they are treated in different subsections.

IV.1 SALT BEDS

Bedded salt deposits are commonly believed by those unfamiliar with them to be massive, thick, pure beds of the mineral halite (NaCl), and this is the usual basis for model studies. Though there are a f local places where such beds can be found, most salt beds are more t cally somewhat thin-bedded, may alternate with other evaporite deposit such as anhydrite ($CaSO_4$) or other salts (of the KCl-$MgCl_2$ groups), and are frequently separated by thin beds of shale. Salt is commonly interbedded with limestones or dolomites or may interfinger with them laterally. Salt beds may also grade laterally into sandstones.

On a microscopic scale, it can be seen that many halite crystals contain liquid (brine) or solid (anhydrite) inclusions. A recent report by Roedder and Belkin estimates the volume of these inclusions to be less than 1% but "an additional possibly even greater volume % fluid is present <u>in situ</u>, filling intergranular pores."(3)

There is abundant evidence for post-depositional recrystallization, differential solution, redeposition in cross-cutting veins, and mass flowage in evaporite deposits. The textures produced in salt beds by these processes increase the heterogeneity produced by depositional processes. There is also ample evidence of solution channels being established along veins and lithologic breaks.

Because salt is so soluble it rarely crops out at the surface; thus its stratigraphy and detailed lithology are mainly known from drill hole records. Though individual distinctive laminae have been traced for long distances through the study of drill cores, most of our information comes from geophysical logs of drill holes or shallow seismic profiles. Neither is adequate to show the amount and number of thin shale, anhydrite, or limestone breaks in salt beds. For this reason, site testing needs a carefully designed drilling program that includes provision for continuous coring that would detect all lithologic breaks. No geologist can predict the presence of a truly homogeneous bed of salt 30 m thick without such a drilling campaign plus detailed, including microscopic, study of the core samples to determine their brine and solid inclusion content.

Realistic estimates of water and brine content of salt beds are critical to proper estimation of the fate of canisters sealed in a salt repository, for, as indicated earlier, such hot briny solutions may effectively corrode the metal canister, leach the HLW matrix, and transport dissolved radionuclides. Water content is also important in affecting the creep rate of salt.

Recent experiments in the Experimental Geochemistry and Mineralogy Branch of USGS by D. B. Stewart and others(4) have shown that at 200°C, water in a rock salt including potassium and magnesium components can contain approximately 70 wt % of dissolved salts. This implies that as little as 1 wt % H_2O in a salt bed may yield fluid that is 3 wt % because of the high concentration of the solution. The dissolving power of such brines should not be underestimated. We know from many hydrothermal experiments that because of changes in hydrolysis constants and the association of ion pair complexes, highly saline solutions at elevated temperatures are highly acidic--the pH can be as low as 2.

It should be noted that the pressure-temperature conditions near the canister may result in the brine becoming two phases (liquid and vapor), which could retard brine access to the canisters. The activity (in a chemical sense) of the brine components would still be the same in the two phases, however, and the liquids would still act as buffers to maintain the corrosive attack on the canisters.

These solutions would strongly attack any metal and effectively leach glass. There is also the possibility that permeation of these solutions along glass grain boundaries and incipient fractures would speed up devitrification, which would then feed back positively to enhance leaching.

Because of the high density of the canister, it might sink in any salt bed that contained the above quantities of saline water solutions, being corroded and leached as it moved downward. Many beds of salt overlie permeable limestone formations and the canisters might end up there, in the path of ground water movement. Any lithologic breaks in the salt might impede that movement depending on the thickness and the rock strength. But solution movement may also be enhanced along those very breaks.

We emphasize the importance of knowing the water content of salt beds proposed for repositories, particularly with the background and the experience at Lyons, Kansas, where considerable volumes of water migrated in an unpredicted manner. That problem arose as a consequence of dissolution of salt by ground water seeping into the repository. Seepage was along an abandoned drill hole that, like most, had not been cased and plugged. This puts a premium on picking a site where precise locations of all abandoned drill holes or old underground workings are known.

Though remote sensing techniques seem likely to be able to spot some surface manifestations of these underground penetrations to supplement state and company records, it remains to be proven by ordinary double-blind experiments that such detection is highly accurate. In this connection it is necessary to prove not only that holes identified from aerial photographs are in fact there, but also that all holes actually have been identified from the photograph--no mean task. If this assurance cannot be made, then modellers of repository behavior will need to take into account the probability of leakage of water into salt through such old holes.

Any abandoned drill holes discovered may disqualify a site if they cannot be properly plugged and sealed. If the well has penetrated the salt there may be a cavernous dissolved region around the hole. In addition, most such wells will show extensive caving of weak rocks in the section, which might provide an efficient vertical transfer path among various aquifers. Since metal casing cannot be guaranteed against corrosion over the time scales we have to consider, some impermeable and chemically inert cement to grout and plug the hole must be developed. This indeed may be an important requirement for any drill holes designed to explore a site for a future repository.

IV.2 SALT DOMES

Of all the geologic media suggested for the underground isolation of HLW from the biosphere, the rock salt in the dry domes of the Gulf Coastal Plain seems mechanically best for disposal (permanent isolation by backfilling and sealing) but probably not for long-term storage and ready retrievability. Room-and-pillar mining in salt is cheap relative to that in hard rock.

Given the time frame of a million years, one cannot claim that the probability of any geologic event is absolutely zero. However, the risks of catastrophic events like destructive earthquakes and volcanism, or of sudden, unpredictable changes in the secular rate of erosion, or of continental glaciation are evidently extremely small in the coastal regions of Texas and Louisiana, certainly as unlikely as they would be anywhere in North America.

Once a critical thickness of overburden had been achieved, Gulf Coast domes grew more or less concurrently with the deposition and loading of the sediments above them. Since the rock over onshore domes is now being eroded, further growth ("diapirism") should not be expected. There is no obvious reason why the coastal plain should not remain tectonically stable for at least another million years.

Below the superjacent cap rock, the lithology is remarkably uniform. Although bedding may have been contorted (it is not always so), the rock is typically free of open fractures. Although its lateral extent is limited, the salt is several kilometers thick, and it should be possible to identify a repository site at least 1000 m from the closest water-bearing strata.

Some (though not all) salt domes appear to be remarkably dry and to have been so for some millions of years. Professor Robert R. Unterberger of Texas A&M University has been probing domes with 40-cm radar. In a dry salt mass like that of Grand Saline in northeast Texas, he is able to map reflections at the boundaries with surrounding water-bearing strata, as much as 2 km distant from the transmitting antenna. He could not do so if the average water content exceeded on the order of 0.1%. (In the "wet" Weeks Island dome, on the contrary, attenuation of the signal is so high that no reflections are recorded, and he turns to sonar.) In a dry dome no lateral migration of ground water appears to have occurred over several millions of years. It is hard to imagine how any ground water could reach the repository and, hence, how any radioactive elements could reach the biosphere.

In a dry dome, the bulk density of the encapsulated HLW would presumably exceed that of the salt, so that containers would tend to migrate downward, all to the good, even if the high-temperature viscosity of the salt were low enough to permit significant movements over the relevant span of time. Thus disposal in salt domes is likely to be permanent.

We do not know whether the sinking will tend to "focus" the canisters, although this effect should be amenable to computation. By focusing we mean that the originally horizontal array will have not only a temperature gradient that decreases away from each canister site, but also a higher-than-expected local temperature at the center of the condensed array. As the canisters sink in the salt, will they be "refracted" inward toward each other? If they are, the central temperature would rise, leading to still faster sinking and focusing until very high temperatures indeed might be reached. This possibility should be studied. There is also an important corollary: additional production of HLW by sub-critical or even, conceivably, critical activity with the U, TRU, and water. We do not suggest that this will happen, but rather that the question be properly addressed. Enough is now known to permit a computational assessment.

Salt is a valuable mineral resource, but worldwide reserves are virtually limitless, so there is no logical reason why a single dome should not be perpetually withdrawn and dedicated to HLW disposal. The possibility of human intrusion at a far future time cannot, however, be discounted.

IV.3 SHALES

Just as most salt beds are not pure and monolithic, shales are rarely homogeneous and uniform. A typical shale is a rock that is more or less silty and contains occasional interbeds or laminae of permeable siltstone or sandstone. Other shales may be interbedded with limestone or dolomite or grade into a calcareous shale and then into a shaly limestone.

To varying degrees shales may be thinly bedded or show fissility, the ability to break into thin sheets. They may also be cut by systems of joints and fractures, and, where the shale is traced into areas where the rocks are metamorphic, may show incipient fracture cleavage. It is just now becoming known that fracture cleavage in many shales is related to original conditions of sedimentation and early diagenesis that make it susceptible to breaking along certain zones. In general, the older and more physically and mineralogically altered the original mud becomes, the more brittle the resulting shale becomes.

Since approximately 70% of the sedimentary rocks of the earth are shales, it is not surprising to find a great many thick shale sections. Yet it is extraordinarily difficult to find one that is uninterrupted by interbeds of other, generally more permeable, lithologies. As in the case for salt beds, it is difficult if not impossible to get an accurate detailed log of a vertical section of most shales from outcrops because of their rapid weathering in most climates and topographies. At the same time, geophysical methods are inadequate to pick up fine interbeds and interlaminations. As thin as these may be, frequently on the order of a few millimeters in thickness, there is good geological evidence that there has been sufficient water flow through these laminae to alter the clay mineralogy in the sandstone whereas the more impermeable shale is unaltered. Hence a requirement for a shale repository must be the acquisition and careful study of drill cores.

Shales are particularly susceptible to mineralogical alteration that promotes physical change if they come in contact with solutions of a different kind than they were naturally bathed in at depth. Shales are complex mixtures of quartz, feldspar, several varieties of clay minerals, zeolites, carbonates, sulfides and oxides. Any significant chemical reactions of these minerals are likely to weaken the physical structure and promote cracking and disintegration at the relatively low confining pressures of a repository. All of these reactions are promoted by increase in temperature.

Before any detailed plans for a shale repository can be drawn, the stratigraphic and mineralogical-geochemical work has to be done. The detailed stratigraphy and petrography we know how to do, but the study of how altered mineralogy affects physical structure is in its infancy. Long-term heating to 300-500°C is likely to induce mineralogical changes including dehydration of smectites. This dehydration could liberate significant quantities of free water and induce textural changes that might be reflected in fracture patterns, which in turn affect the fluid permeability of the formation. We cannot as yet predict such behavior of a specific complex mineral assemblage from general rules.

The USGS has done a fair amount of work on the merits of the Pierre shale of the Dakotas as a possible repository. The stratigraphic and mineralogical-chemical knowledge of the Pierre shale is possibly greater than that of any other shale in the world. We know that there are thick shale sections in it and that it has a generally stable mineralogy. On the other hand, as much as we know, we still are unable to predict with any high probability what the fluid permeability is of such a section after long-term heating by buried HLW. And we are not able at this time to define how rare and how thin occasional interbedded silt laminae would have to be to prevent significant fluid migration in or out of the formation. At this time we could not rule out extensive fluid migration via fracture permeability following a 10-20-year period of moderate heating.

IV.4 GRANITE

Because they are widespread, underlie large regions of the mountain belts and shield areas of North America, are relatively homogeneous, have high crushing strengths (up to a few kilobars at low confining stress), low porosities and, therefore, low pore-water contents (0.01 to 0.03) and low permeabilities (10^{-7} to 10^{-17} cm^2), granitic rocks have good potential for development as high-level waste repositories. Large granite plutons range in thickness from 2 km to 15 km and, unlike sedimentary rocks, are not likely to have aquifers at depth. Retrieval of HLW canisters would be easier in granite than in most other rocks. However, granites are brittle, and we currently know neither their behavior under thermal stress nor their sorptive properties.

Many of the important physical properties of granite are site-specific, such as joint density and state of stress. Other site-specific features such as hydrothermal alteration zones, dikes, quartz veins, the irregular three-dimensional geometry of the granite body itself, and faults will all contribute, along with the joint pattern, to the hydrologic regime. It is the Panel's opinion, and apparently that of several foreign countries as well, that a sizable body of granite underlying a hydrologic basin of appropriate dimensions may prove, in the long run, to be an excellent underground repository. We know of no reasons, as yet, to rule it out. Research on granites should be pushed vigorously, particularly because there may be either socio-political or geological reasons why burial in salt may be ruled out. In this case it appears that we have no fall-back position, and granite is an obvious alternative.

IV.5 BASALT

The presence of tens of thousands of square miles of up to a 5,000-ft-thick succession of plateau basalts in the northwestern United States, and their nearness to the Hanford, Washington and Idaho National Engineering Laboratories Waste Storage facilities have focused attention upon these rocks as potential HLW repositories.

Fresh massive basalt will have crushing strengths as high or higher than those of granite, and porosities, permeabilities, and linear thermal expansion coefficients that may be as low or lower. The coefficient of thermal conductivity for basalt and granite lies in the same range (5×10^{-3} to 8×10^{-3} cal/[cm][sec^2][°C]), but basalt is likely to be the higher of the two.

Although the laboratory-measured physical properties of granite and basalt thus seem to be roughly equivalent, there are geological differences in their mode of occurrence that favor the former rock over the latter. The typical basalt flow of the Columbia and Snake River plateaus ranges from 10 m to 45 m in thickness, and is often separated from the overlying and underlying flows by an aquifer. Lower columnar and upper fan-type jointing of each individual flow is characteristic, and most lavas have a 5-m thick vesicular zone at the top, and a 1-m thick vesicular zone at the base of each flow. Thus it seems that, on the average, basalt should be far more porous and permeable than granite, and that it would also offer a higher risk of contaminating the ground water if used as an HLW repository. Advantages of some basalts would be their lateral continuity over hundreds of square miles, and the fact that some of the rocks are slightly altered and contain clays or zeolites, which may enhance the sorptive properties of the basalt. Unfortunately, though there are some data on clay minerals and zeolites, there are no published data on the sorptive properties of well-described altered basalts.

The general feeling of the Panel is that because of geologic constraints, establishing a safe repository will be more difficult in basalt than it will be in granite. Finding a thick unfractured or unjointed basalt flow that can be opened up and resealed without the development of fractures that will communicate with an actual or potential interflow aquifer may be a requirement that is difficult to meet. Again, we know enough about the areal geology, stratigraphy, and general lithologic character of basalt, but would need means to determine the site-specific fracture permeability or bulk retentivity. At a minimum, a strong laboratory reconnaissance program would be needed in order to demonstrate the desirability of further consideration of basalt.

IV.6 OTHER ROCKS

It is appropriate at this point to comment briefly on other rock types that may have excellent potential as disposal hosts but have been largely ignored up to the present.

Analysis of thousands of water well records in places such as New England demonstrates that the flow of ground water in bedrock in these areas is entirely fracture-dependent, and that metamorphic rocks have very low porosities and negligible permeabilities. With increasing degree of metamorphism, such rocks become increasingly anhydrous and granular textured, approaching the igneous rocks in their general physical properties. High-grade metamorphic terrains are common in many mountain belts, as well as in areas such as the Minnesota Shield, the South Dakota Black Hills, and the Adirondacks. In the latter region they are associated with igneous rocks such as anorthosite, gabbro, syenite, and charnockite, all of which are composed of anhydrous silicates and all of which are potentially usable depository hosts.

Dunite, a relatively uncommon igneous rock occurring in parts of the Appalachians and the Coast Ranges, has the unique property of being potentially self-healing. Access of water to an HLW canister in these rocks would result under the pressure and temperature conditions of burial, in the development of serpentine; the large volume increase accompanying this reaction would help to make the repository impermeable. It would need to be shown, however, that the process itself would not induce fracturing.

In a similar way, a proposal by Professor W.S. Fyfe that canisters be surrounded by a packing of MgO powder (which would hydrate to brucite--$Mg(OH)_2$--upon contact with water) is also worth considering as a safeguard against possible waste leakage.

PART V: SOLUTION TRANSPORT THROUGH ROCKS

The principal barrier to contamination of the biosphere by HLW is the time delay expected during the migration of the nuclides through the rock unit that contains the repository. This delay can be predicted from experimental data plus some assumptions regarding the particular setting, or from evidence of previously completed "experiments."

The first approach is based on data concerning three key factors: the actual rock permeability in situ, whether this be true permeability or flow through fractures; the flow rate; and the retardation, if any, of the dissolved nuclide relative to the flow of the water. Part VI will consider the first two factors. In this section, the third factor will be discussed and then the previously completed "experiments."

V.1 SORPTION OF RADIONUCLIDES ONTO ROCK MATERIALS

Critical to the operation of a secondary barrier to radionuclide migration is the ability of a rock through which fluids may slowly flow to adsorb or react with dissolved radionuclides. There is now an abundance of experimental data on the extent of adsorption of various fission products and transuranics by soil and rock materials. Unfortunately these experimental data are useful only in a general way and even then may be misleading.

The reasons are that for any such surface chemical process, the nature of the mineral surface must be specified precisely (mineralogical and chemical composition, surface area per unit of mass) and the experiment must be carried out under conditions similar to those expected underground. In addition, for experimental results to be meaningful a uniform methodology would have to be employed so that various materials and different elements could be compared on a sound common basis.

The experiments thus far performed have been on materials described variously as "desert soil", "tuff", "basalt", or "montmorillonite", to mention a few. None of these terms is a precise description that would allow anyone to infer what the chemical behavior of the material might be. "Montmorillonite" is a term used in many different ways by clay mineralogists and rarely to describe a specific mineral with a fixed composition and crystal structure. Specific standard clay minerals (American Petroleum Institute Standards) have been used, but only for the sake of comparison and not to give the impression that they are standard mineral types. Adequate description of any clay is made only by chemical analysis (either bulk or electron microprobe) coupled with crystal structure analysis by X-ray diffraction. Since the methods of sample preparation strongly influence surface area, these too must be specified. The ion-exchange capacity and selectivity of the clays used must also be determined.

The same comments apply to the use of rock terms such as "basalt" or "tuff", which are just field terms of gross lithology used for the convenience of the geologist mapping in the field and not in any sense the same as quotation of the precise chemical formula of a reagent.

Results of experiments conducted at 25°C and 1 atm. pressure are not a good guide to what might happen at 100°, 200°, or 300°C. We know of temperature-induced reversals in cation selectivity, exchange capacity, and sorption characteristics that are a result of surface configurational changes. In addition, all of these data are almost meaningless unless some realistic choice of solution is made. Formation waters of deeply buried rocks tend to be rich in dissolved solids, and this ionic strength can greatly alter sorptive properties of mineral surfaces. Cation adsorption is generally competitive, and radionuclides may be passed unsorbed if competing cations of formation waters have already been sorbed strongly onto surfaces.

What we can say with the information at hand is that we would expect certain classes of materials to be more retentive than others at room temperatures. Thus desert soils would have high retentivity and granites and salt low retentivity; with tuffs, basalts and shales lying between, we would expect notable cation exchangers, such as smectites and zeolites, to be highly retentive. But this is no quantitative basis for estimation of what will really occur in a specific formation at depth and at elevated temperatures. Before that can be done we need a carefully planned and executed program of testing by experimentation.

V.2 FIELD "EXPERIMENTS"

An alternative method to predict behavior of HLW transport through rocks is to examine natural settings where such transport might have occurred. Two such cases have been studied in some detail and can shed some light on the process. These are the Oklo natural fission reactor discovered in Gabon, and the underground nuclear explosion test, Cambric, carried out in Nevada.

Approximately 1.8 billion years ago a uranium ore deposit experienced the appropriate conditions of U concentration, ^{235}U concentration, and H/U ratio for it to go critical and yield fissions and energy. This is known as the Oklo phenomenon. The four to six local zones where this occurred are thought to have produced 15,000 megawatt years (MW yr) of energy, over a period of approximately 0.5 to 1 million years. The site has been studied in order to determine the extent of loss of the various fission products and TRU's that were produced during and subsequent to the time fission was occurring.

The results indicate that the losses were largely dependent on the chemistry of the nuclides in question. Alkalies and alkaline earths were lost either completely or in very significant amounts. These would include the major fission product nuclides of concern, ^{90}Sr and ^{137}Cs [see Lancelot et al.(5)] On the other hand, the radioactive rare earth elements and the TRU's largely remained in or near the reactor zones.(6) A very precise material balance is not possible. It would not be surprising if 10% or 20% of the products in a given reactor zone had been lost.

The difficulty with the interpretation of the Oklo event is the lack of precise geological control. It is not clear to what depth these deposits were buried at the time of the fission reaction. Some believe that the process was going on under fairly shallow burial, because the water that acted as a moderator had to be vaporized and this could only happen close to the surface. The sediments have been altered by heat and pressure to a state suggestive of burial to approximately 4,000 ft,[7] although there is a suggestion that the depth may be as much as 6 or 7 km. The mineral assemblages, their compositions, and their fluid inclusions all suggest a variety of possible depths of burial so that no sure conclusions can be drawn. It is likely, however, that the depth was considerably more than the 1,500 ft envisioned for HLW burial.

The uncertainty concerning the depth of burial means that it is not possible to make a direct comparison of the Oklo phenomenon with an HLW disposal site. This is so both because of the dependence of the flow of fluids on depth (and the consequent variation in degree of openness of cracks) and because the distance that the nuclides would have traveled to reach the surface is not known.

Whatever the depth, however, there must be serious concern over the loss of the major fission products, ^{90}Sr and ^{137}Cs.

The second "experiment" is the Cambric nuclear test in Nevada and the subsequent water pumping tests conducted using drill holes at the site. The massive pumping tests conducted in the decade since the explosion have shown that the radioactivity that has entered the water is in very low concentrations. This is very encouraging.

Two factors that play a role here, however, make the test less relevant to HLW containment. The first is that much of the radioactivity is in a glass produced by the extreme heat of the explosion. This glass has had ten years to devitrify and be leached. Since little radioactivity is detected in the pumped water, it can be inferred that the nuclides are being retained. The problem is that the water is cold, and the pumping continues to bring cold water to the site. This test, therefore, is not using waters that are comparable to those anticipated in an HLW repository: hotter than 300°C and with high ionic strengths. As a result, the channels through which the water is flowing are behaving like pipes. Further, the very low concentrations of nuclides are partly due to the rapid flow rates, which serve to dilute the nuclides as they are released.

PART VI: RADIONUCLIDE TRANSPORT FORECASTING

The objective of the transport modeling considered in this analysis is to forecast the subsurface movement and evolution of radionuclides emanating from a radioactive waste repository under various hypothetical situations. Perhaps the most challenging aspect of this problem is the necessity to forecast over long time periods (250,000 years)[8] with uncertain information. In addition to the elements of uncertainty concerning the transport listed previously,[9,10] the following also play a role:

- hydrologic characteristics of the site (primary versus secondary permeability and porosity, hydrodynamic dispersion),
- mathematical representation of subsurface transport, and
- solution of the resulting equations for realistic physical conditions.

Many of these uncertainties have been encountered in petroleum engineering and subsurface hydrology. In these instances, uncertainty is reduced primarily through the "calibration" process whereby the mathematical model and its input parameters are modified until a historical record (pressure history, concentration trends) is reproduced within a range of error deemed to be "acceptable." Obviously, the simulation of radioactive waste transport does not, in general, lend itself to a "calibration" form of uncertainty reduction. In summary, the problem is one of either minimizing the uncertainty outlined above such that a deterministic analysis (inclusive of sensitivity analysis) can be meaningful, or alternatively, incorporating this uncertainty directly into the analysis so that the decision-maker is cognizant of the degree of uncertainty inherent in the forecasts.

VI.1 STATE OF THE ART OF TRANSPORT MODELING

Two operational models are currently capable of simulating the movement of multiple radionuclides in the subsurface. These models have been developed for the Nuclear Regulatory Commission and the Energy Research and Development Administration (now Department of Energy) by Intera Environmental Consultants and Battelle Northwest Laboratories, respectively. (Note that we have not included the model employed by the American Physical Society Study Group on Nuclear Fuel Cycles and Waste Management because of the physical and mathematical simplifications inherent in their approach.) The salient features of the two models are summarized in Table 1. Examination of this information reveals that the Intera numerical model is the most physically realistic and flexible. The BNWL models, however, have the advantage of analytical simplicity and associated computational efficiency.

Burkholder et al.[11] have argued because of the non-reducible uncertainties inherent in some elements of the analysis of radionuclide transport, "that highly sophisticated transport models should be used with caution or

TABLE 1

CHARACTERISTICS OF TRANSPORT MODELS

Model Characteristic	Model		
	INTERA	BNWL I	BNWL II
Dimensionality	3D Cartesian 2D Radial	1D Cartesian	2D Cartesian
Mathematical Formulation	Numerical Finite Difference	Analytical	Analytical-Numerical
Dispersion Representation	Variable, Function of Velocity, Tensor	Scalar, Constant	Scalar, Constant
Convection Representation	General Velocity Field	Constant Velocity Field	Spacially Varying Velocity Field
Species Transported	Multiple Radionuclides	Multiple Radionuclides	Multiple Radionuclides
Transporting Medium	Saturated Porous Medium	Saturated Porous Medium	Saturated Porous Medium
Sorption	Linear	Linear	Linear
Source Dissolution	Variable	Constant	Constant
Chemical Form	Single	Single	Multiple*
Discrete Fracture Representation	None	None	None
Stochastic Capability	None	None	None
Geologic Strata	Non-Homogeneous	Homogeneous	Homogeneous
Temperature Dependence	Density, Viscosity	None	None
Solubility	Limited	?	?

*Under development

perhaps not be used at all." They further state that such models "could create unwarranted illusions of certainty." The significance and importance of this point of view depends, of course, on the interpretation of the phrase "highly sophisticated."

In other branches of science and engineering, the evolutionary trend has been to minimize forecasting uncertainty through improved mathematical representation of the physical system and careful evaluation of associated physical parameters (see, for example, work in structures and mechanics, hydrology, meteorology, etc.). The use of a simpler model, however, is advantageous when numerous alternative scenarios must be examined, such as in a sensitivity analysis or an optimization algorithm. A combination of both approaches, such as utilized by Intera in their report to EPA,(12) represents a cost-effective approach to investigating the problem of radionuclide transport.

VI.2 THE QUESTION OF UNCERTAINTY

There is little question that the models presented in Table 1 represent the state of the art of engineering capability in transport modeling. Certain degrees of sophistication could be included, such as a better representation of the fracture system, but these modifications are not likely to enhance the accuracy of the model forecasts materially, because of the uncertainties that will still remain.

It is more important to consider the possibility of quantifying the uncertainty in the model so that decision-makers are aware of the degree of uncertainty associated with the analysis. The simplest approach to quantifying uncertainty in simulation modeling is through a sensitivity analysis. Such an analysis was performed by Intera for EPA.(12)

In this approach, a range of parameter values is used in the predictions. These are selected so as to encompass the entire range of physically meaningful parameter values. Such an analysis provides an insight into the role of each model parameter on the calculated radionuclide distribution. To conduct such an analysis generally requires a tremendous amount of computational effort. To analyze two levels of the 12 parameters considered by Intera unambiguously would require 2^{12} independent simulations. Because this is prohibitive, even with use of analytical models, a subset of the general problem is normally considered and the results, of necessity, are indicative rather than definitive.

While a sensitivity analysis provides the decision-maker with a range of possible radionuclide distributions, it does not give any insight into the probability of occurrence of any particular forecast. In simulations wherein large residual uncertainties in input are unavoidable, the uncertainty in the predicted radionuclide concentrations should be recognized and quantified. In other words, in an analysis of the radionuclide transport problem, the solution should appear as a confidence region (i.e., we are 95% certain the real concentration of ^{90}Sr lies between x and y, given the probability distributions of the input parameters). Thus, the reliability and importance of the forecast can be directly related to the reliability of the input parameters. To conduct such an analysis requires estimates of parameters and their uncertainty, and a suitable mathematical model.

Standard mathematical models such as presented in Table 1 can be modified for simulation under uncertainty. The procedure, known as Monte Carlo analysis, involves conducting a series of simulations in which parameter values are selected at random from their respective probability distributions. These values are used in simulation runs and the output variables, in this case radionuclide distributions, are assembled into probability distributions. From these distributions, confidence intervals can be computed. Such analyses, however, require excessive computational effort, particularly when several different parameter distributions are involved. Alternative schemes are available to circumvent these computational difficulties, but these cannot be considered at this time to be state-of-the-art engineering methodologies.

While uncertainty in the partial differential equations may be accounted for by use of new mathematical methodology, one must still consider the problem of estimating these uncertain parameters. Whether intentional or by default, these parameters will be subjective probability estimates. Tools are available and currently being developed to compute these estimates by use of objective and subjective information (see, for example, Bayesian methods). The credibility of forecasts made under condition of uncertainty will depend upon a reasonable representation of the probabilistic parameters. The impact of parameter uncertainty, that is the resultant uncertainty in the projections, is dependent on problem and boundary conditions. In example problems that have been considered,[13] situations were encountered in which the uncertainty increased, reached a maximum, and asymptotically decreased to zero as a function of time. Another case resulted in an exponential increase in uncertainty throughout the simulation period. Thus it is apparent that generalizations regarding the impact of parameter uncertainty on forecasts of radionuclide concentrations are not normally possible.

It should also be noted that uncertainties associated with parameters in the governing equations interact in such a manner that their individual contributions to the spread in the confidence interval of the projections cannot be discerned. Thus it is not possible, in general, to delineate unambiguously the importance of the uncertainty associated with, for example, the source term.

VI.3 CREDIBILITY OF THE ANALYSIS

At this point it is evident that uncertainty is the distinctive element of radionuclide transport analysis. While uncertainty is associated to some degree with forecasts emanating from all mathematical models of subsurface phenomena, this uncertainty is generally minimized through calibration with known historical data. Even where historical data are scarce, one generally reserves the option of measuring _in situ_ hydrologic and transport parameters. Because the disposal site has not yet been selected, such measurements are not currently available. Moreover, even after site selection, the in situ measurement of parameters must be minimized to ensure the integrity of the site. Because of the apparent inability to decrease significantly the uncertainty associated with the transport parameters, the only viable alternative is to incorporate as much of the uncertainty as possible directly into the analysis so that the decision-maker is aware of at least the minimal uncertainty inherent in the forecasts.

In evaluating the suitability of available radionuclide transport analyses as a basis for establishing radiation standards for high-level radioactive waste management, EPA should particularly consider the following:

- The existing simulations of radionuclide transport emanating from high-level waste are limited to a small number of hypothetical problems associated with selected waste-disposal scenarios. The results represent qualitatively the movement of the waste under these conditions. Although limited in number relative to the spectrum of hydrological settings possible for a repository, the problems selected represent a reasonable and relatively unbiased choice.

- The problems examined should be considered indicative rather than representative of situations to be encountered in the storage of radioactive waste.

- The relationship between the parameters and processes employed in the model and those to be encountered in a disposal site is very uncertain.

- The Intera model incorporates directly or indirectly (as in the case of fractures) those attributes of the prototype physical system most likely to play an important role in radionuclide transport from a repository. A possible exception is unsaturated transport.

- The credibility of the model and the associated analysis would be enhanced by a satisfactory simulation of radionuclide transport at the Nevada Test Site.

- Current models do not incorporate parameter or process uncertainty in their forecasts.

- The scenarios considered in the analyses are, in large part, arbitrary and may or may not encompass the hydro-geological systems to be encountered at a specific site.

- The general approach currently used by some consulting engineers for forecasting radionuclide transport, though strongly limited by the inherent uncertainty in the hydrogeologic, geochemical and chemical data input, nevertheless represents the best means currently available for establishing the movement of radionuclides if and when the proposed containment is breached and water comes in contact with the waste. We have considered the quality and applicability of the simulation methods but not their adequacy. The adequacy of the forecasts depends on the sensitivity of the decision-making process to the state of the art of transport modeling.

VI.4 PROPOSED RESEARCH

We have been asked to suggest techniques that would result in an improved capability for risk assessment regarding the HLW repository concept. In transport simulation, three areas appear to be prime candidates for further research:

- In order to incorporate the uncertainty associated with parameter identification, a program should be initiated that is directed toward the development of an analytical capability for forecasting under uncertainty. This would not involve great sums of money inasmuch as the primary goal is software development, which is not usually capital intensive. In the short term, it would appear reasonable and appropriate to employ existing techniques for simulation under uncertainty in order to analyze one or more mathematically simple scenarios. This would at least provide a ball-park estimate of the uncertainty associated with the forecasts.

- Before the methodology developed in the preceding step can be utilized, estimates of parameter uncertainty must be available. These estimates can be obtained through an effective utilization of subjective and measured information. The analytical apparatus for this type of analysis is incompletely developed and should be considered a priority element of the research effort.

- Once uncertainty can be quantified and incorporated into transport forecasts, the next major objective is to minimize this uncertainty. This can be achieved primarily through additional field observation. Thus, a primary goal of a research program should be the <u>in situ</u> measurement of hydrological and geochemical parameters. Because of the nature of the repository, this methodology must be compatible with the maintenance of repository integrity. The liberal use of subjective information will minimize the cost and negative impact to the repository of data collection and, it would seem, provide a cost-effective program of parameter identification.

PART VII: GEOLOGIC AND OTHER ACCIDENTAL HAZARDS

Assuming that physical and hydrologic requirements for a safe HLW repository have been established, one must still consider whether all other factors that may disrupt the integrity of the site have been taken into consideration, and whether these factors are tractable to numerical risk analysis. As one report states, "At some point in the repository site and emplacement method selection and safety assessment, whether willing or not, we will quantify in order to make decisions."(14) Without attempting to assess all non-geologic and geologic hazards, we shall comment briefly on some of them, primarily to illustrate the extreme numerical uncertainties attached to most.

VII.1 NON-GEOLOGIC ACCIDENTS

VII.1.1 Intrusion by Man

The development of an underground waste repository involves the breaching of what was probably initially an intact geologic container. After the repository has been backfilled, heating combined with the possible access of ground water will set up a convective hydrological system in which ionic transport rates will also be greatly accelerated. These features, as well as uncertainty about the long-term effectiveness of having sealed shafts in bedrock, are matters on which there are very few bases for judgement.

Intrusion of a repository at some future date in the search for mineral materials, including the uranium and TRU elements that were buried, or to satisfy archeological or other curiosities appears to us also to be a risk for which no trustworthy probability estimates may be applied for the time span over which the integrity of the repository is to be assured. Material demands shift with technology. The most successful civilizations last for only a few millenia at best, and even these are not without their disastrous interludes. Man's unpredictability far outstrips most of the imagined geologic hazards we can foresee, and we doubt that it is amenable to meaningful probability analysis.

VII.1.2 Meteorites

An astronomic risk that is generally cited is meteorite impact. The earth annually receives an infall of approximately 10^6 tons of cosmic dust, but meteorites large enough to produce craters the size of Meteor Crater in Arizona (1.2-km diameter), or larger, are estimated to have a frequency on the order of 1 per 20,000 years or less. The bedrock in a meteorite crater is pulverized to a depth of approximately one-tenth of the crater diameter, but the surrounding and underlying rock will be highly fractured. If one assumes conservatively that a repository at a depth of 0.5 to 1 km might be breached if it lay within a radius of 10 km from the point of meteorite impact, and also that the probability for impact is equally distributed over the earth's surface (5.1×10^8 km^2), the likelihood of meteorite damage is approximately 3.3×10^{-11}/yr, or 1/30,000 averaged over a million-year time span. Meteorites, therefore, should not be regarded as significant factors in evaluating repository safety. A more detailed treatment by Arthur D. Little, Inc.[15] yields similar results except for secondary effects such as stream diversion by impact. Given the need to make provision in the repository for major water table variation, this problem can also be given low significance.

VII.2 GEOLOGIC ACCIDENTS

The structure of the earth and energy sources that drive its physical processes are such that stochastic models are not widely applicable, unless one closely restricts the area of inquiry, and probably the time as well. We are aware that fault tree analysis is the numerical basis for risk assessment in the Rasmussen report on nuclear reactor safety.[16] However the question of assessing engineering failure by a surface facility over a 30-year time span is not the same problem as assuring geologic and hydrologic integrity at an underground site over a million-year time span, especially because there is information on reactor performance in the past.

VII.2.1 Extrusive and Intrusive Magmas

Aside from gradual subsidence of the Gulf Coast and the Mississippi Embayment commencing approximately 70 million years (m.y.) ago, and the isostatic depression and rebound of the northeastern and north-central part of the country in response to continental glaciation, the United States east of the Rocky Mountains has been geologically stable for approximately 100 m.y. In this vast region the youngest dated igneous rocks (dikes) have an age of approximately 70 m.y. For this entire area, then, the probability for a magmatic incursion into a waste repository during the next million years has to be taken as astronomically low but numerically uncertain.

Along the entire Cascades chain, by contrast, the probability for a volcanic eruption may be on the order of 10^{-2}/yr. If there are an estimated 65,000 km^2 of potential volcanic terrane and a repository within a 10-km radius of a volcano might be adversely affected by an eruption, the average rate of risk per 300 km^2 is on the order of 10^{-4}/yr. However, it obviously makes a difference whether we designate one of these 300 km^2 areas as lying close to Lassen Peak, Mt. Baker, Mt. St. Helens or Mt. Ranier, or remote from them. Even for the remote areas, it is well to recollect that no one predicted or could have predicted the May, 1943 eruption of a new volcano at Paricutin, in the western Mexico volcanic belt.

For the area of intermediate magmatic risk lying between the Rocky Mountain Front and the Cascade-Coast Range Belt, there is no very good basis for speculating on numerical risk probabilities, nor is there any ready answer to why areas such as Sunset Crater, Arizona, and the Craters of the Moon, Idaho, have been active within the past few thousand years.

The situation with respect to magmatic hazard typifies what the Panel believes to be true of most other geologic risks. Within different specified regions we may estimate a relative order of danger, but for very few areas can we have any confidence in orders-of-magnitude estimates of risk probabilities. Of all the world's volcanoes now under surveillance, Kilauea is one of the few whose short-term behavior is predictive. Even here, projections for a million years in the future are well beyond the current state of the art.

VII.2.2 Earthquakes and Faults

Even in regions of transform faulting where great earthquakes occur relatively frequently on the geologic time scale, like the active, western continental margin of North America, we cannot yet predict specific events of magnitude 7 or more with precisions better than about 100 years and 100 km. We do know, however, that the recurrence rate of events on the San Andreas fault has been on the order of 200 years over the last few thousand years, that geologically rapid displacements are still going on, and hence that California is obviously a high-risk region where we would not place a repository if we fear the hazards of earthquakes.

On the other hand, we cannot claim that the probability of an earthquake is identically zero anywhere in the world because the origins of earthquakes in the interior of the continent (New Madrid, 1811) or at its passive margin (Charleston, 1886) remain pretty much a mystery. Had these events occurred a few generations earlier, before written records became available, we would not now be worried about destructive earthquakes in the central and eastern United States. About all that we can confidently say is that the earthquake risk is much less in some regions, say the Gulf Coastal Plain, than it is elsewhere, say along the trace of the San Andreas fault and its subsidiaries.

The hazards of earthquakes may well be overly exaggerated. Recent surveys by Professor H. Dowding of Northwestern University and Dr. Howard R. Pratt of Terra Tek reveal that damage to underground openings is very much less than that to surface structures immediately above. Disruption would occur if a seismogenic fault actually transected an opening, but adequate site characterization should have eliminated this eventuality. Thus, once a repository has been sealed and its surface facilities abandoned, the effects even of large earthquakes are likely to be negligible.

It is well to recall that the earthquake history of the United States is based chiefly upon diaries or newspaper accounts, which may cover a time span varying from 300 years to a few decades, depending upon the area. The development of a widespread instrumented seismic network with sophisticated equipment and data processing is partly an outgrowth, during the past three decades, of the interest in detecting nuclear bomb b[illegible]ts. Instrumental seismology has existed for decades, but systematic [illegible]a compilation is relatively recent. On either basis, whether from an incomplete historical record stretching backward for up to three centuries, or from a compilation of seismic record data, perhaps adequate for only three decades, there is little reason for confidence in forward predictions covering a million years.

During the past three decades a series of qualitative seismic risk maps has been produced by the Coast and Geodetic Survey, the most recent of these in 1969. Responsibility for the next set of risk maps lies with the U.S. Geological Survey, but their own estimate is that a <u>reliable</u> seismic probability risk map lies a decade or more in the future. Even this assessment may be optimistic.

VII.2.3 <u>Glaciation, and Climatic Changes</u>

Geologic records of glaciation in Alaska extend backwards for at least 10 million years and in the coterminous United States for more than 2 million years. Despite the generally adopted statement that there were only four major cycles of glaciation, it has now been demonstrated that there have been numerous glacial epochs, that they follow a cyclicity on the order of 10^5 years, and that they are predominantly controlled by the earth's orbital eccentricity, as proposed long ago by Milankovitch. Both theory and the now established record show that the bulk of these 10^5-year cycles represents glaciation for the Northern Hemisphere, with interglacial periods like the present one lasting on the order of 10,000-20,000 years. The current interglacial was established between 16,000 and 11,000 years ago. It is now predicted that the long-term trend for the next 20,000 years is toward extensive glaciation in the Northern Hemisphere. Although this forecast is in accord with climatic analyses that show a consistent cooling trend for the past three decades, the latter trend is too short to permit interpretation that the two are coupled.

The near certainty that re-glaciation will occur long before any disposal site will have fulfilled its assigned role, implies that there will be other complications. The depth of bedrock scouring by ice sheets averages only 20 ft. However, re-routed streams have incised bedrock for depths of up to 200 ft; Niagara Falls, the best known example, has excavated a 170-ft deep trench for a length of 7 mi during the past 10,000 years. Waxing icecaps cause isostatic depression of bedrock amounting to hundreds of feet, potentially producing faulting; waning icecaps allow isostatic rebound, more potential faulting and, with extreme melting, a good possibility for flooding continental margins to depths of [illegible] or more above present sea level.

Mean precipitation and evaporation differ markedly between glacial and interglacial times. We cannot assume that an area that is arid today will remain so during a glacial cycle. This is most obviously the case in Utah and Nevada where, during the recent glacial epochs, there was a pronounced pluvial environment. What such a pluvial environment might do to the hydrologic regime in the site of an HLW repository seems to have been largely ignored in current risk assessments of repositories such as Hanford and the Nevada Test Site.

The Panel believes that continental re-glaciation has a very high probability of occurring within the time period of concern for HLW and that the associated climatic changes will have differing effects on waste repositories, depending on location. There may, however, be certain advantages to locating repositories in areas likely to be re-glaciated, because this would effectively seal them from intrusion several thousands of years hence.

A different problem arises from the potential combustion of coal and petroleum products. This, the so-called greenhouse effect, would be a warmer world-wide climate created by the CO_2 resulting from fuel burning. Even if the effect were not total melting of the Antarctic and Greenland ice-sheets, sea level would rise significantly. The evaluation of salt domes as repository sites should include consideration that such an eventuality is possible. If the top of the dome were accessible to sea-water, extensive dissolution of the salt could occur, possibly exposing the HLW. Further, even if the greenhouse effect did not play a role, it is known that sea level has varied for different interglacial epochs and could be higher next time than it is now.

VII.3 FUTURE RESOURCE EXPLORATION

Although the energy supply appears to loom as the major mineral resource problem for the next few decades, this is only because its present urgency has diverted attention from the far more important question of how the world's rapidly expanding population can maintain the raw material supplies necessary for an industrialized society. Current annual consumption of newly mined mineral products is 3.75 MT per person, and by 1985 this figure will have doubled. Geochemical and economic arguments have been adduced to show that when the average ore grade of a metal slips below a critical level, the amount of energy needed to extract that mineral will far exceed any costs that society can reasonably pay for it, so the mineral will no longer be available. Mercury, silver, gold, copper, and lead are candidates for such early scarcity. The 1975 National Academy of Sciences Report of the Committee on Mineral Resources and the Environment has concluded that technology cannot always close the gap between rising demands and available resources, so we shall be inexorably driven to lower ore grades, larger tonnages, and other materials.

As an illustration of the enforced shift to increasing tonnages of decreasing grade we may cite uranium, for which the 1990 projected demand of U_3O_8 is 700,000 MT; production of this amount of U_3O_8 will be possible only if the present ore (economically mineable) grade (0.22% U_3O_8) falls to 0.075% in 1990.

From what is known of the world's mineral resource picture, it is difficult to be optimistic that industrialized society can sustain itself at anything approaching its current levels in the next millennium. A steady decline in the quality of life appears inevitable, as well as an increasingly desperate exploitation of raw materials. What the mineral exploitation might be like a thousand years from now is impossible to predict.

Of the rock types currently under consideration as hosts for HLW repositories, shale and basalt seem unlikely to assume an important economic role. Granite is somewhat different because there are some granites that po[illegible]ially are mineable because they contain relatively large amounts of thor[illegible], uranium, and rare earth. Several other types of ores are also associated with granites.

The most likely targets for near-term exploitation, however, are salt domes because of the potential productivity of petroleum, halite, and sulfur; and bedded salt deposits because of their potash, halite, and gypsum. The United States has only 4% of the world's total proven potash reserves, and most of these are concentrated in the New Mexico area now being evaluated as an HLW repository. Future conflicts between the demand for HLW repositories in bedded salt and the needs of agriculture for potash seem inevitable, and may even now constitute an important negative socio-economic factor in the development of some repositories. Such conflicts could be minimized in the case of salt domes by selection of domes that are barren of petroleum and sulfur.

VII.4 OTHER GEOLOGIC HAZARDS

Some data on rates of uplift and denudation may be used to underscore the unpredictable nature of so-called steady-state geologic processes. The average rate of regional denudation in the United States (0.063 m/10^3 yr) is such that it would require approximately 15 million years to uncover an HLW repository at the burial depths now planned. This seems to be such a large safety factor that we could easily relegate denudation to the status of a relatively minor risk. However, denudation rates vary by factors of up to 75, depending on climatic and topographic factors, so there is a large uncertainty in applying averages that are not site-specific.

Assuming that a repository is planned for a stable area of the continent, we may now ask how certain we are of this stability. The Adirondacks, long regarded as an ancient stable shield area, are now known to be rising at the rate of 3.7 mm/yr in the center of the mountains. The beginning of the rising of the Adirondacks is not well dated, but at the present rate of uplift the 1,600 meters of maximum uplift, and subsequent deep erosion, could have taken place within a half-million years; but it could also, of course, have taken millions of years longer. Prior to the initiation of this recent uplift, there would have been no reason to predict that this large area of the United States would be rapidly uplifted and eroded. There is also no basis for predicting where, or when, other such uplifts may occur on the stable shield of the continent. The point is that there is a finite but very low probability that a repository buried at a depth of 0.5 km almost anywhere might, within a relatively short time, unpredictably reappear at the earth's surface. How one can make an orders-of-magnitude conjecture concerning these probabilities is beyond the Panel's ability to resolve.

PART VIII: MONITORING THE REPOSITORY

Part of the responsible establishment of an HLW repository is the provision for a warning system in the event of loss of some of the HLW to the biosphere. If we assume that some form of monitoring for radioactivity will be mandatory, there are two aspects to this problem: early warning to permit some attempt to repair the site or confine the spread of the HLW, and longer range surveillance to provide warning in sufficient time to reduce exposure to the contamination. The first type of monitoring would be done close-in to detect early signs of the breach of the repository. For the second, more widely spaced monitors would be used.

Any close-in monitoring would, of necessity, include some connection with a surface-recording device, a means for replacement or repair of the sensor, and due consideration of the possibility that the sensing scheme itself could provide an additional pathway for migration of radionuclides. That monitoring be continued for a period of time on the order of at least several centuries for the fission products and one million years for the TRU wastes is a commitment that it is not reasonable to expect future inhabitants to fulfill.

There is no known instrumentation that has demonstrable reliability for decades, much less for centuries. Beyond those times, the radioactivity is much less, will have a large alpha component, and the sensitivity of any currently available instrumentation to the losses would decrease markedly just when the sensitivity needed for detection would increase. The commitment must be to a repository that may be monitored remotely for some period of time, but we shall not know what is going on within the general confines of the repository once the monitors left in place malfunction.

Remote monitoring can be effected both from the surface and from the drill holes made to help define the site to begin with. However, such monitoring cannot define any activity such as migration that is occurring in the repository. A new technology would be needed to achieve this, and such a technology would first have to be shown to be possible.

An analysis of the nature of remote monitoring arrays pinpoints the very difficulty that predicting the direction and rate of migration of the HLW poses in the first place. Even if the overall hydrologic regime were well determined, small deviations from the average flow might still result in the arrival of some HLW at the surface. Such short-circuits could contain only a small fraction of the total HLW, but they could still have serious local effects. It is rarely possible to identify where such effects might occur, thus they are potentially hazardous even beyond the confines of the fenced-off reservation of a repository. We see no way to predict such occurrences either in time or space. It is not part of our charge to consider risk tradeoffs that might arise in the case of small numbers of people being at potentially serious risk in such cases. Consideration of this problem should be included in any monitoring scheme.

If our prediction of the behavior of a repository were quite accurate, we could allow for small losses that take sufficiently long times to arrive at the biosphere reservoir so as to be below presently specified maximum safe levels. However, owing to the variable hydrologic regimes that would almost surely occur over the next million years, the leaks of the HLW might occur significantly earlier than predicted, but still much beyond any time when continuous monitoring can be anticipated. The TRU wastes that enter the biosphere undetected at such time in the far future might impose serious risks on our descendants.

PART IX: CONCLUSIONS

It should be emphasized that our intention is not to recommend what may be the best host rock or geographic location for HLW storage or disposal. Our intention is to identify gaps in the state of geological knowledge that may prohibit reasonable predictions to be made about events and processes that might occur in certain host lithologies. In some instances we feel compelled to indicate potential problems.

(1) Knowledge concerning the properties of the salt in dry domes is good. If the HLW canisters are not to be retrieved after the 5 or 10 years needed to complete the filling of the repository, then the short-time deformations in dry salt domes around the canisters can be computed and reasonable predictions are possible. Disposal would be permanent because at the expectable high temperatures, the high-density canisters would probably sink into the salt. The usual assumption seems to be that the salt is indeed dry. This is clearly not so in certain bedded deposits or in all domes. Careful measurements of water content will be most important. Further, even dry salt contains some water, so that the sinking of canisters computations, with the possibility of "focusing," should be done with this in mind.

(2) Retrievability of HLW in other rock types is not so much a question of locating the canisters because they have bodily moved elsewhere, but being able to collect all of the waste because corrosion and leaching might so disintegrate the canisters that much of it is dispersed. This problem is further exacerbated by the possibility of dispersal by fluids far away from the site. We believe that the appropriate computational methods for assessing such possibilities are known, but our knowledge of the access of the repository system to fluids via transport through cracks is not now adequate. Research is needed on how to determine the extent to which a repository is an "open" system. As a consequence, while several lithologies are potentially viable candidates for repositories that permit retrieval, not enough is known to permit a selection or priority assignment.

(3) There is a fundamental paradox to be encountered in the design and construction of a "closed" repository. It is desirable to avoid disturbance of the rock mass by exploration drilling as this provides extra pathways for the HLW to reach the surface. However, one must determine ly precisely the geometric distribution of rock properties throughout the future repository site and its immediate surroundings. Prior to excavation, only careful examination of many drill cores can possibly delineate these properties. These two contradictory demands must somehow be resolved. Proper assessment may have to await excavation of shafts

and adits, despite the high risk of the capital investment should the site then be found to be unsuitable.

(4) If the HLW is not reprocessed, U and Pu will pose long-term radiation hazards, as well as a different chemistry of transport. It is unlikely, however, that the integrities of the canister, its contents, and its immediate surroundings will last very long, whether or not reprocessing is carried out. We have seen no evidence of survivals longer than a decade. The question of reprocessing does relate to the mix produced and thus the temperatures to be expected in the canisters as a result of the heat production from that mix.

(5) We are surprised and dismayed to discover how few relevant data are available on most of the candidate rock types even 30 years after wastes began to accumulate from weapons development. These rocks include granitic types, basalts, and shales. Furthermore, we are only just now learning about the problem of water in bedded salts, and the need for careful measurements of water content in domes.

(6) The state of knowledge concerning total permeability in jointed shales, granites, and basalts is still inadequate for meaningful forecasting. Total permeability includes all paths for fluid migration through the rock, including cracks, joints, faults, and inhomogeneities of lithology. The lack of such knowledge does not necessarily imply that a rock is unsuitable. Comparatively anhydrous rocks in the granitic clan or basalts might well be the best rock types for storage, and perhaps disposal, even though they are jointed and salt is not. Transport properties depend on both the chemical and mechanical nature of the rock.

(7) Two principal questions arise for all lithologic types other than the salt in domes:

1. How does one determine the real "permeability" of the rock mass surrounding the repository and extending to the surface, and

2. How does the permeability of the fissures affect solute-retardation factors relative to the flux of water throughout the rock mass?

Development of methods to answer the first question will be very hard, but must be undertaken. The plethora of distribution coefficient and retardation coefficient data now available provide a good start, but they are not adequate to address the critical problems of retardation under conditions of high ionic strength.

(8) Existing computational methods for assessing transport may well be adequate, and the accuracies of these models can be specified in principle. However, until the uncertainties of the input parameters are included in the numerical models, the reliability of any model remains undemonstrable. Further, while mathematical simulation of radioactive ion transport from the repository is an important and very useful tool in the risk analysis of an HLW repository, such simulations can be dangerously misleading unless careful attention is directed toward inherent physical and mathematical assumptions. Of particular concern here is the relatively superficial attempt to date to incorporate parameter uncertainty in the contaminant transport forecasts. It is of paramount importance that the analyst present unambiguous estimates of uncertainty in such forecasts so that decision-makers are not misled into believing that such forecasts are independent of parameter uncertainty.

(9) It seems clear that the uncertainties of forecasting the behaviors of conceptual HLW repositories are due principally to inadequate knowledge of the relevant mechanical, radiochemical, and hydrologic properties of the candidate rock types. Most of these can be measured by well established methods, but times required even for adequately funded research efforts are likely to vary widely--from a year or so to a decade or more.

As noted in the text, there are also several questions, notably the determination of real permeabilities and porosities in the rocks at a site, or the nature of the long-term monitoring systems, answers to which must await the invention of new technology. The time scale for such research is much less readily determined.

Except for the modest effort on salt, the geological aspect of the HLW repository problem had largely been neglected by our generation until a year or so ago. It will not be solved without a strong commitment of money and manpower, lasting beyond 1985.

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LIST OF ABBREVIATIONS

EPA	U.S. Environmental Protection Agency
HLW	High-level radioactive wastes
OWI	Office of Waste Isolation
DOE	U.S. Department of Energy
ERDA	Energy Research and Development Administration
NRC	Nuclear Regulatory Commission
BNWL	Battelle Northwest Laboratories
USGS	U.S. Geological Survey
LBL	Lawrence Berkeley Laboratory
LLL	Lawrence Livermore Laboratory
TRU	Transuranic
m.y.	Million years
m	Meter
MT	Metric ton
ft	Foot

GLOSSARY

Adit: A nearly horizontal opening by which a mine is entered, drained, or ventilated.

Alpha particle: A positively charged particle emitted by certain radioactive materials. It is made up of two neutrons and two protons bound together, hence it is identical to the nucleus of a helium atom. It is the least penetrating of the three common types of radiation (alpha, beta, gamma) emitted by radioactive material, being stopped by a sheet of paper. Alpha particles are dangerous to plants, animals, or man only if the alpha-emitting substance has entered the body.

Anhydrous: Free from water, especially water of crystallization.

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

Bars (pressure): Absolute unit of pressure in the cgs system equal to 1 dyne per square centimeter.

Beta particle: An elementary particle emitted from a nucleus during radioactive decay, with a single electrical charge and a mass equal to 1/1837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is called a positron.

Biosphere: Zone at and adjacent to the earth's surface where all life exists.

Bittern: The residual liquids left after crystallization is complete.

Calcine: Product of calcination wherein materials are heated to a higher temperature under oxidizing conditions but without fusing.

Diagenesis: The physical and changes that occur to sedimentary rocks. In the history of a sedimentary rock there is no point at which change stops, such as occurs in the solidification of a molten igneous rock. Thus are changes that occur with sedimentary accumulations are known collectively as diagenesis.

Diapirism: The forceful intrusion of one geologic material into another; overlying geologic material.

Devitrification: Crystallization from a glassy phase. Glass is an unstable substance. Because its components are spaced without plan, at unequal distances, the forces of attraction that surround a "particle" are unbalanced. Ultimately, the components respond to the unequal stresses and are drawn together to form crystals. This process is known as devitrification.

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

Formation waters: Water that exists in the intergranular or fracture space in rock formations.

Gamma rays: High energy, short wavelength electromagnetic radiation. Gamma radiation frequently accompanies alpha and beta emissions and always accompanies fission. Gamma rays are essentially similar to X-rays but are usually more energetic and are nuclear in origin.

Half-life (radioactive): The time required for one-half of an initial radioactive material to undergo nuclear transformation, the half-life is a measure of the persistence of a radioactive material and is unique to each radionuclide.

Halite: Impure common salt, NaCl.

High-level waste: The highly radioactive waste resulting from the reprocessing of spent fuel to separate uranium and plutonium from the fission products. The term includes the high-level-liquid-wastes (HLLW) produced directly in reprocessing, and the solid high-level-wastes (HLW) which can be made therefrom.

Laminae: Thin geologic layers, plates, or scales disposed in layers like the leaves of a book.

Lithologic: Pertaining to the characteristics of rock formations such as layering.

Magma: Molten igneous rock.

Montmorillonite: A mineral resembling clay consisting of an hydrous aluminum silicate with considerable capacity for exchanging part of the aluminum for magnesium, alkalies and other bases.

Pluton: Very large masses of igneous rocks that extend along the cores of most major mountain ranges and underlie vast areas of the ancient shield or central stable areas; sometimes called batholiths.

Salt dome: A type of geologic structure resulting from the upward thrust of a great salt mass through overlying rock layers. The resulting salt form is roughly cylindrical and in some cases has resulted in observable uplift at the earth's surface.

Smectite minerals: Clay minerals.

Tectonic: Of or pertaining to the formation of the earth's crust; the forces involved in or producing such deformation and the resulting forms.

Transuranic elements: Elements with atomic number greater than 92. They include neptunium, plutonium, americium, curium, and others.

Zeolite: Any of a family of hydrous silicates, which have capacity to act as ion exchangers.

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