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Isolation of Radioactive Wastes in Geologic Repositories: Status of Scientific and Technological Knowledge

A Working Paper for the Interagency Review Group on
Nuclear Waste Management
prepared by the
Subgroup for Alternative Technology Strategies

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1. INTRODUCTION

The purpose of this paper is to describe the issues pertaining to the scientific and technological knowledge relevant to the construction, operation, and ultimate sealing and long-term safety of a mined geologic repository for radioactive wastes. (Other disposal techniques will be examined in other papers of the Subgroup for Alternative Technology Strategies of the Interagency Nuclear Waste Management Task Force.) This paper identifies areas where we have confidence in our current state of knowledge, and also areas where uncertainties and lack of knowledge still exist. Included to the extent possible will be an evaluation of the significance of such knowledge gaps and identification of of areas where work is currently underway or needed to resolve uncertainties.

Radioactive wastes considered in this paper are generated as a result of processes within a fission reactor, whether it be a civilian nuclear power plant, a research or test reactor, or a plutonium production reactor. Two major classes* of radioactive nuclides comprise such waste:

(1) Fission products: These isotopes are the fragments produced when a heavy nucleus is split. The bulk of the radioactivity is associated with radionuclides that change to stable elements over a period of several hundred years. The fission products produce intense radiation and are a major source of the heat generated during the first few hundred years of the disposal period. A few fission products have half lives of millions of years, but these constitute a minute fraction of the initial amount of radioactivity.

(2) Actinide elements: These consist of uranium which has not undergone fission, transuranic elements formed by neutron capture, and the

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* In addition, carbon-14 and other radioactive isotopes created by neutron activation of materials may be present in the wastes.

decay products of these two types of elements. Actinides generally have considerably longer half-lives than fission products and an equivalent mass generates considerably less heat per unit time. However, integrated over time the actinides can contribute significantly to total decay heat (about half of the total heat in high-level wastes and more than 90 percent of the total heat in spent fuel).

These two classes of radioactive nuclides occur in several distinct combinations that are candidates for disposal by emplacement in mined geologic repositories. One combination is found in spent reactor fuel, comprised mostly of uranium oxide with zircalloy cladding but also, with a burnup of about 30,000 Mw(th) days/metric ton, containing waste in the form of about 1 percent transuranic elements and about 3 percent fission products (1). Under current U.S. policy to defer indefinitely commercial reprocessing for recovery of uranium and plutonium, the possibility exists that large quantities of spent fuel will at some time be disposed of as waste (2). Assuming a nuclear power economy of 380 GWe in the year 2000, the spent fuel discharged through that time will contain approximately 98,000 metric tons of uranium and other actinides (3).

A second combination of radionuclides is found in the high level waste streams from the chemical reprocessing of spent fuel. Reprocessing has occurred in government facilities, and a large quantity (70,000,000 gallons) of reprocessing waste, the radioactive part of which is composed of roughly 98 percent fission products and 2 percent actinides, has been accumulated (3). A relatively small amount of high level commercial waste (612,000 gallons) from the now closed commercial reprocessing plant at West Valley, N.Y. also awaits treatment and disposal (4). If commercial reprocessing is initiated in the United States, the major waste product requiring disposal will be high level wastes from the nuclear power fuel cycle, rather than spent fuel. The composition, by weight, of high level waste from commercial power plant fuel (i.e., from once-through PWR fuel having an exposure of 33,000 Mw(th) days/metric ton) would be about 84 percent fission products and 16 percent actinides (5).

The third combination of waste nuclides of interest to this report are contained in scrap and trash, which in the course of a wide variety of nuclear activities, have become contaminated with plutonium and other transuranic nuclides. Large quantities of this so-called TRU waste have been buried in trenches at the Hanford, Savannah River, and Idaho reservations and whether this should be exhumed and removed to a deep geologic repository is under review. TRU wastes with a concentration of transuranic nuclides above 10nCi/gm have been packaged and stored in a dry environment above ground since the early 1970s. Fifty thousand cubic meters of this material have now accumulated in retrievable storage at the Idaho Falls site and elsewhere (3). Because the long life of the TRU components requires this material to be isolated from the biosphere, these wastes, though of low heat generation rate, must be isolated in much the same way as high level waste.

Each of the three major categories of waste--spent fuel, reprocessing waste (from Government or from commercial operations) and TRU--have different radionuclide compositions and, therefore, different chemical and radiologic properties. These variations in properties and their possible interactions with host rock are discussed in Section 4A.

A comparison of the thermal power and radioactivity of spent fuel (SF) and high level waste (HLW) that typically would result from the light water reactor fuel cycle is shown in the following table (11):

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Time Since Discharge of Spent Fuel, Years	Thermal Power watts/MTHM (a)		Radioactivity Ci/MTHM (a)	
	SF	HLW	SF	HLW
10	1200	1000	410,000	320,000
100	290	110	42,000	35,000
1000	55	3.3	1,800	130
10,000	14	0.47	480	42
100,000	1.1	0.11	58	21
1,000,000	0.39	0.15	21	10

a. MTHM is metric tons of heavy metal orginally charged to the reactor.

The composition of the high-level waste assumes recycle of uranium (not plutonium) to light water reactors (LWRs) and removal during reprocessing of 100 percent of the tritium and noble gases (He, Kr, and Xe), 99.9 percent of the iodine and bromine, and 99.5 percent of the uranium and plutonium. The fuel is assumed to have been reprocessed one year after removal from the reactor. The spent fuel has appreciably higher thermal power and radioactivity than the high-level waste, primarily because of the presence of the plutonium and its subsequent daughter products.

The as-generated TRU waste averages about 9 grams of plutonium per cubic meter. The volume can be reduced by a factor of about 50 by incineration (and, therefore, the plutonium concentration increased by the same factor). The heat generation rate and radioactivity of the contained plutonium as a function of time since purification (separation from daughter products) are as follows (11):

Time Since Purification, Years	Thermal Power watts/MT of Pu	Radioactivity Ci/MT of Pu
1	200	120,000
10	230	84,000
100	220	7,700
1000	52	1,600
10,000	14	440
100,000	1	35
1,000,000	0.2	9

The above data show that the thermal power and radioactivity of the TRU wastes change much slower with time than does spent fuel or high-level wastes. This, of course, is the result of the comparatively longer half life of transuranic radionuclides.

Nuclear waste management involves the effort to identify and develop the means to isolate these wastes from the biosphere. The different options that have been seriously considered for the isolation of radioactive wastes can be divided into two general categories:

(1) Elimination of portions of the waste from existence on earth, such as by transmutation and by ejection to space, and

(2) Disposal of the wastes in various geologic media, either in the continental rock mass or in the seabed.

The approach that has received most attention to date, and which is the subject of this paper, is disposal in a geologic cavity mined by conventional technology. Such a mined cavity is commonly referred to as a geologic repository.

The safety of a mined geologic repository is generally analyzed in terms of three time periods:

(1) Operational period: While the repository is open and during which any emplaced waste can be retrieved by conventional mine machinery.

(2) Thermal period: For high level waste, the first few hundred years or for spent fuel the first few thousand years after closure of the mine during which time radioactive heat production will be significant.

(3) Actinide decay period: A period that exceeds several hundred thousand years, defined by the ultimate decay of the actinide isotopes.

Relevant issues for the operational period before the repository is permanently sealed include the possibility of repository flooding, the venting of radioactive gases and/or flammable gases emanating from the waste or from waste/container/host rock interactions, the capture of water vapor from air within the repository, the question of retrievability, and the effects of thermal stress on the integrity of the repository.

The thermal period is of special interest because it is during this interval that the thermal effects will be at their maxiumum. As the near-field temperature of the repository rises and then falls during this period, the repository contents and surroundings will be subjected to thermal, mechanical, chemical and, possibly, thermoelectric effects. Most physical or chemical changes within the waste form that would affect the relationship between the waste and its container, or between the host rock and its container, will proceed at the highest rate during this period. The initial thermal expansion will place the immediate host rock and its surroundings under stress and could conceivably provide a means for breaching the containment by fracturing the rock, and then permitting subsequent intrusion of water.

The third and final time period extends from the end of the thermal period until the risk of the repository has disappeared. While the stresses generated during the preceding period will have ended, the long half-lives of the plutonium and other actinides results in a continuing but gradually diminishing level of risk. It is over this much longer time period that our predictive capabilities are the least accurate.

The length of the period during which the waste should be considered hazardous is an issue for which there is a broad range of views. It has been discussed by several workers (6-10), who variously conclude that it may be from several hundred to several million years. A comparison of the relative ingestion hazard of high-level waste with that of uranium ore (6) led some to suggest that several hundred years of isolation would be sufficient. At the other extreme of the time scale, it has been suggested that neptunium-237 and its daughter products might require isolation from the biosphere for several million years (7).

Isolation for roughly the first 1000 years, in which time most of the fission products will have decayed to stable isotopes, is a minimum requirement. Beyond that, one might conclude that the wastes should be isolated from the biosphere for as long a period as possible, hopefully for periods longer than several thousand years and, preferably, for several tens of thousands of years. Complete confinement need not be assured for this long a period if we understand the release and transport processes adequately to feel confident that total releases will be small and that transport to the biosphere will be so small as not to result in an unacceptable risk to humanity.

In the following sections this report considers first a set of perspectives on waste disposal and then discusses in turn the issues important during the operational period of a repository, factors that affect the isolation of the waste in a repository, the methodology for and our ability to assess the long term risks associated with possible releases from the repository, and questions relating to site selection and characterization. The report closes with a discussion of the properties of the various candidate host rocks.

2. PERSPECTIVES

The task of accurately predicting the fate of radionuclides emplaced in a repository over time frames of even several hundreds to many thousands of years is unprecedented. The principal earth science disciplines involved in such a task -- namely hydrogeology, geochemistry and rock mechanics -- are relatively young sciences with little experience in making or evaluating predictions that cover time frames even as short as a few decades. Numerous limitations of our knowledge in these fields, pertinent to radioactive waste disposal, are identified throughout this paper. Nevertheless, we believe that such gaps in our current knowledge need not rule out successful underground containment of radionuclides for periods of many thousands of years. The reasons for this belief follow:

(a) application of the multiple barrier concept to repository selection and design can compensate for the lack of total understanding of repository behavior;

(b) wastes can be allowed to cool and/or be fabricated to take account of the physical properties of the host media prior to their emplacement in the repository;

(c) the knowledge gaps, enumerated in various sections of this report, do not necessarily all apply to a specific repository nor are they of equal importance;

(d) the pertinence of some of the perceived knowledge gaps probably will be resolved during construction and operation of the repository and conservative engineering practices can sometimes be utilized to compensate for remaining uncertainties; and

(e) active R&D programs focused at filling knowledge gaps, currently are underway or planned and our understanding of the relevant hydrogeology, geochemistry, rock mechanics, and risk assessment should increase rapidly over coming years.

These reasons are discussed below in the order listed.

The utility of a design and site selection philosophy that relies upon a series of backup systems to provide redundant protection in the event of the failure of a key component -- the so-called multiple barrier concept -- is a widely accepted approach in engineering practice, particularly in areas with limited empirical information. For example, a geologic environment combining long groundwater flow paths, slow groundwater velocity, rocks with high sorptive capacity along the flow path, and tectonic stability is an example of the multiple natural barriers that are able to contribute to radionuclide retention. Multiple barriers may also be "engineered." Examples include the inertness of the waste form, corrosion resistance of the canister, and the character of the material packed around the canisters. Although efficacy of these man-made multiple barriers will undoubtedly be shorter than those provided by nature; they could still be useful in some geologic environments, particularly in the first, and, probably, the second time period.

To date emphasis has been placed predominantly on the importance and suitability of a particular rock type to contain radioactive wastes and relatively less on the system comprising the entire hydrogeologic and geochemical environment.

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A change in emphasis appears necessary. both for implementation of the multiple barrier concept within the repository and for optimally conducting a search for appropriate repository sites.

Heat emitted by the wastes during the first several hundred to few thousand years is a major cause of containment uncertainty during this time period. Adjusting the waste content of high level waste canisters, altering the repository loading factors, and cooling the wastes for several decades prior to emplacement in a repository can reduce the uncertainty of the response of the waste, the geologic media, and groundwater to this heat. The Swedish proposal for placement of reprocessed wastes in granite, for example, calls for lower waste concentration in high-level waste canisters than has been considered in the United States and the cooling of high-level, reprocessed wastes for 40 years prior to emplacement. Cooling, spacing, and dilution of the wastes would also permit consideration of geologic media (for example, zeolitized tuff or alluvium) that have low heat conductivity but excellent sorptive properties for radionuclides. The advantages of some surface cooling of the wastes are clear and current plans involve some cooling period before emplacement in a repository. Just how long the wastes should be cooled for optimal operation of the total waste management system is a question that requires further study.

In addition to cooling, fabrication of the wastes to make them compatible with the physical-chemical properties of an intended host medium is still another way to reduce some of the uncertainties (outlined in other sections of this report) related to the integrity of the waste form.

The knowledge gaps enumerated throughout this paper do not necessarily apply at every potential repository site, nor are those gaps applicable at a given site of equal importance. For example, the potential for radionuclide transport upward via the shafts, fractures induced by the shaft construction, or exploratory drill holes may not constitute a major concern in a terrain in which natural groundwater movement is predominantly downward. Similarly, uncertainties about waste form solubility are of less importance in an hydrogeologic and geochemical environment that provides long groundwater flow paths, slow water velocity, and strata of high sorptive capacity.

Some of the matters perceived to be potential problems may be resolved by knowledge gained empirically during construction and initial testing of a repository. Science traditionally advances by a steady interplay of theory, experimentation, methodology development, and demonstrations (empiricism). Although theory clearly dictates what data and problems are pertinent, theories are themselves adjusted to fit anomalous facts, and facts themselves are, sometimes, fleeting. It may be necessary to run a variety of in-situ tests or, perhaps, even to construct and operate a repository for a decade or longer to resolve the question of the importance of currently perceived gaps in our knowledge, as well as to test new methodologies being developed for site characterization. Problems remaining after such a testing period will, hopefully, lend themselves to resolution by conservative engineering design.

Although knowledge requirements are addressed throughout this paper, a brief general comment is appropriate here. Some current in-situ tests of rock properties are not conducted at actual or potential repository sites. Such studies provide useful generic data on rock properties and are important for instrument development and data interpretation on methodology. However, the variability of geologic data and the systems philosophy dictate that generic characterization cannot substitute for detailed studies at actual repository sites. Such site-specific work, including in-situ heater tests (initially conducted with electrical heaters), will necessarily take considerable time (at least a year) and money to construct, and many months to a few years to operate and interpret. Accordingly, in the future, greater program emphasis should be placed on conducting such tests in areas that can be identified as candidate sites.

3. THE OPERATIONAL PERIOD

During the period when the repository is open several considerations are important; these include the safety and cost of operation, the monitoring of repository phenomena, and the prevention of occurrences that could jeopardize long term isolation.

3A. Flooding

A sudden flooding of the repository workings could cause serious immediate problems. The potential for flooding depends on the local hydrology and design features of the facility, and can be minimized by careful site selection, by conservative engineering and by monitoring during the drilling and tunneling operations. Sufficient hydrologic and mining knowledge exists to reduce this problem to a very low level of risk.

3B. Gaseous Effluents

Any toxic or explosive gas (e.g., hydrogen, methane, and hydrogen sulfide generated by chemical reactions within the repository could be controlled by the mine ventilation system and should not become a safety hazard (12). The release of radioactive gases (e.g. krypton-85, tritium, and iodine-129, which are present as a relatively low fraction of the total radioactivity of spent fuel and an even lower fraction of the radioactivity of high-level and TRU wastes) to ventilation corriders probably can be controlled during operation of a repository by engineered barriers to flow and diffusion.
The extent to which this might be necessary would depend on the amount of radioactive gas that is likely to be released from the repository and on the level of emissions permitted by environmental regulations (13,14). The former depends on the waste form and integrity of the waste container and on possible interactions among the

waste, its container, and the host rock. Relatively little attention has been given to repository conditions. Corrosive interaction between the spent fuel and the host rock could be very important.

High level waste would release relatively little radioactive gas (essentially only that from spontaneous fission of the actinides) because the original gaseous fission products would have been removed and captured during reprocessing. The gaseous wastes that are captured and concentrated during reprocessing could be encapsulated, normally converted to stable solid forms, and, also, be isolated in a geologic repository.

3C. Water

For some host rocks, particularly salt, minimizing the amount of free water within the repository could be very important during the first period and could even provide the limiting factor for long term confinement. Depending on the amount of naturally contained water in the formation and the limits of free water required to assure safety, it might be necessary to dehumidify air circulating through the repository for ventilation. Dehumidification can readily be done by standard industrial techniques.

3D. Retrievability

Maintaining retrievability involves tradeoffs for a repository designed for disposal rather than for storage of radioactive wastes. On the one hand, there might be safety advantages in sealing the storage chambers as soon as they are full. On the other hand, to hedge against the possibility of design, engineering or construction errors or other unanticipated difficulties, there might be reason to maintain fairly simple retrievability for a period of time. In salt and possibly in shale, the repository openings will have a natural tendency to close because of the plastic flow that results from the increase in temperature and from the weight of the overburden. Maintaining retrievability beyond a few years or decades will involve some additional cost. It is not yet clear how to optimize the tradeoff between the early backfilling and sealing of a storage room and letting the rooms remain "open" for ease of retrievability. An analysis of this issue is required.

A repository could also be used to store spent fuel in a retrievable mode in order to maintain the option of reprocessing at a later time. If maintaining retrievability for a few decades would lead to additional problems with respect to flooding, water absorption, radioactive gas effluents, or other factors affecting safe operation of the repository, the cost and feasibility of handling these problems will need to be compared with the costs and risks of other options including wet and dry surface storage. The cost and risks of transportation must, of course, be included in such analyses. Although the 1978 DOE Task Force (3) recommended against operating a repository for economic retrievability, this option requires more analysis to provide perspectives on cost and safety.

3E. Rock Mechanics Considerations

From a structural viewpoint, a geologic repository for radioactive waste is not conceptually different from previously mined cavities. Underground facilities have been built and operated for many centuries. Some of the mined cavities have remained open to this day, despite the fact that they were not constructed for long-term stability, while others have collapsed or filled with water. An important observation with respect to these cavities, however, is that, except for the opening, no significant change has been made on the geologic formations in which the cavities exist. Within a waste repository a thermal pulse will be generated by the radioactive decay of the emplaced wastes. Because of the potential for this thermal pulse to alter the structure of the surrounding rocks, knowledge of the response of the host rock and its surroundings to the thermal loading is of major importance. The potential far-field and long-term effects and their implications will be discussed in Section 4C on rock mechanics under long-term isolation. Here, only short term effects are considered.

Rock mechanics as applied to repository design is well advanced for repositories in salt (15-17). The major mechanisms for mechanical deformation of salt have been determined and the laws governing these effects have been identified. The major design factor for which rock mechanics must provide analysis is plastic deformation that affects the repository openings through creep mechanisms. The analytic models needed to predict the near-field response of the rock mass have been developed with data obtained from laboratory experiments and from in-situ heater testing conducted in Project Salt Vault (18) in Kansas. The validity of applying these models, developed for bedded salt conditions, to dome salt will be determined through in-situ heater test experiments being conducted at Avery Island (15).

Uncertainty remains, however, about the specific data required for a rock mechanics analysis. For example, experiments with single crystals of salt at high temperature and pressure could be utilized to establish a rock mechanics model. But, single crystals of salt constitute a material of high purity with specific slip systems available for mechanical deformation and a unique temperature-deformation relationship. By comparison, rock salt from a geologic formation is an impure polycrystalline material. Its strength and deformational characteristics are influenced by the presence of impurities, solid solution, and grain boundaries. The strength is greater than that of single crystals and the time-dependent behavior is different. Also, rock salt is more resistant to the effects of an increase in temperature than single crystals of salt. Nonetheless, by employing appropriate engineering conservatism, current knowledge with respect to rock mechanics is adequate to successfully design repositories in salt.

Numerical analysis of rock mechanics questions in non-salt formations is also being actively pursued (15, 19-24). The most important problem that must be solved for hard rock formations is that of identifying and experimentally confirming the potential failure modes. In-situ experiments underway in granite in Sweden and at the Nevada Test Site and those planned for basalt at the Hanford site in 1979, are intended to establish the mechanisms of deformation in these rocks. The major design consideration in hard rocks is brittle fracture. The approximation of continuum mechanics that has been applied effectively to salt may not provide a good aproximation for a repository developed in a jointed and fractured rock mass.

It is of major importance to distinguish between individual rock specimen and rock mass properties. The appropriate means of correlating these two types of samples is still undergoing technical and engineering debate. Most data currently available are based upon laboratory experiments and measurement on individual rock specimens. These data are not completely adequate for engineering design because they represent the individual specimens and not the rock mass; the latter commonly contain fractures and heterogeneities that could significantly alter the response of a structure built in such a geologic environment.

The program of the Department of Energy in rock mechanics emphasizes those items related to site-specific design and development of instrumentation that will be reliable over the time required to conduct in-situ tests. Experiments will be developed to measure in-situ properties of the rock mass for non-salt rocks including mechanical properties and the time and temperature dependent relationships. The primary objective of the program is to provide data that can be used to validate the analytical models which describe the response of the "rock mass" in the near field. As recommended by the NAS Panel on Rock Mechanics(25), experiments capable of inducing large scale failures are being planned and will be undertaken in 1979. The specific goal of these experiments will be to provide the conceptual basis for defining permissible stresses, pillar stability, deformation and failure modes in the near field. In addition, two major experiments with radioactive waste are planned for Hanford (26) and the Nevada Test Site (27) to evaluate both thermal and radiologic effects.

4. LONG TERM ISOLATION.

As discussed above, the ability of a repository to assure long term isolation of nuclear waste depends on the effectiveness of the various natural and engineered barriers. These can be aggregated into three categories: (1) barriers against disintegration of the waste form and container, (2) barriers provided by the host rock and the surrounding rock mass, and (3) barriers provided by the length and character of the hydrologic flow path from the repository to the biosphere. These will be discussed in this section in turn.

4A. Waste Form and Waste-Rock Interactions.

Chemical and radiological interactions between the host rock with its contained water and both the waste form and the container could lead to disintegration of the packaging and partial dissolution of the waste. The extent to which this will happen depends on the nature of the container and the waste form, the chemical properties of the host rock, the ground water, and the duration of exposure. Research work has been underway for more than two decades to evaluate container materials and to develop processes for producing stable solid forms for high-level and transuranic wastes (28). The development and assessment of container systems for spent fuel has begun only within the last year. Substantial further progress on containers and waste forms awaits performance criteria and the results of ongoing experimentation.

The current reference form for high level waste assumes that the waste is homogeneously distributed in a borosilicate glass which is then placed in a container of mild steel (for disposal in salt) or stainless steel (for disposal in most other formations). One problem with borosilicate glass is that some highly soluble phases are produced as the glass devitrifies. There is also recent evidence (29) that contact with pressurized water at the 200-400 degrees C temperatures that could occur near the waste in the early years of storage rapidly alters the borosilicate glass and promotes interactions between waste and both shale and basalt rocks. Examples of interactions are the formation of a uranyl silicate directly from hydrothermal alteration of the glass and the reaction of cesium and sodium from the waste with aluminosilicates in basalt and shale to form pollucite, a stable cesium sodium aluminosilicate mineral.

Investigation is underway on potentially more stable waste forms, such as synthetic inorganic polycrystalline materials (e.g., ceramics, oxides and silicate minerals) that might prove to be more resistant to radiation and to chemical attack in a given geologic environment (30). Several years of research and development will be required to advance oxide and silicate crystalline forms as a competitor to borosilicate glass. Even more complex waste forms such as metallic matrices, cermets, and microspheres of waste coated with impermeable pyrolytic carbon (31-33) are under study. More corrosion resistant container materials, such as Hastelloy C and alumina, are also being considered for waste emplacement in salt (34). The efficacy of coating of a metallic container with flame sprayed oxides (e.g. alumina) or silicate glazes has yet to be evaluated. A total of three to five years probably will be required to develop an adequate understanding of chemical reactions between candidate waste forms, container materials and the chosen geologic formation.

The current reference concept for storage of spent fuel assumes that one or more fuel assemblies will be placed within a container of mild or stainless steel that is filled with helium and sealed by welding. Substantial (at least several years) work remains to be done to experimentally determine allowable temperatures to avoid excessive failure of the fuel rods, to avoid criticality problems if fuel material is loose in the container, and to measure interactions of the container, the zircalloy cladding, and the fuel pellets with potential host rocks. More needs to be known about the chemical forms of the fission products and actinides in the spent fuel pellets and cladding or about the resistance of these forms to leaching or interaction with repository environments. Research work on these problems is underway by Lawrence Livermore Laboratory, Rockwell Hanford Co., and the Battelle Pacific Northwest Laboratory.

The age and concentration of high-level wastes and the age and exposure (burnup) of spent fuel determines their rate of heat generation and their surface temperature. These parameters, in turn, affect the severity of the thermal pulse to the host rock and the nature of the geochemical interactions between the waste and the host rock. The duration of the pre-disposal cooling time is, therefore, an adjustable parameter that can be lengthened in order to reduce the rate and severity of some impacts of the waste on its surroundings. The spacing between canisters and the concentration of wastes within each container can also be used to control the magnitude of the thermal pulse.

The effects of gases that are generated by the wastes over the long term must also be considered. The primary means for minimizing release of radioactive gases (e.g. krypton) to the atmosphere would be to provide engineered barriers (such as the plugged shafts and boreholes) to flow and diffusion. Gases resulting from corrosion and waste-rock interactions (e.g. hydrogen, hydrogen chloride, and chlorine) will, most likely, be accommodated by diffusion through grain boundaries, flow through fractures, or dissolution in ground water.

Currently, transuranium wastes (containing contaminated trash such as paper and neoprene gloves) are normally enclosed in mechanically sealed steel containers. A problem with this type of waste is that it generates combustible gases (e.g. hydrogen and methane) by radiolysis and pyrolysis during storage. These gases escape gradually from the unwelded containers relieving pressure during storage, and could be troublesome within a repository. The organic materials in these wastes might also react with the actinides to form compounds that are less likely to be sorbed by the surrounding rocks. For these reasons it may become necessary to incinerate these wastes and to fix the ashes in an inert solid material such as glass, concrete, or a synthetic mineral. The choice of waste container and waste form could be made and the related R&D completed within several years after the incineration question (currently under review by the D.O.E.) is resolved.

The current status of knowledge and research and development programs on waste-rock interactions was the subject of a recent conference (35). The chemical interactions between waste and host rock, the effects of temperature and the presence of a fluid phase, are best understood for salt (18). Even so, additional work is needed on the complex chemical properties of brines and bitterns containing many ionic species. This is underway at the USGS and the Oak Ridge National Laboratory (15). Because of salt's highly corrosive nature, currently planned waste containers would seem to be breached and substantially corroded by all but the very driest salt within months to years. Current work may be able to extend the period of integrity to decades but waste packaging in the case of salt is now generally assumed to provide only for safety during transportation and for ease of retrievability over a relatively short time span.

Less is known about the chemical properties of other candidate host rocks at the relevant temperatures and pressures and little is known about the interaction of waste with these rocks. However, there are indications to suggest that at least in some other media (granite and basalt are examples) the container and associated overpack material might be expected to maintain their integrity for much longer times. Investigations are now underway on basalt at Rockwell-Hanford and Pennsylvania State University, on granite at Lawrence Berkeley and Lawrence Livermore Laboratories, on shale at Sandia Laboratory, Georgia Tech and Pennsylvania State University and on tuff and alluvium at Sandia (15,35). The interactions with waste of several of these media are also being conducted in other countries (35).

The host rock provides the first natural barrier to waste migration and strongly influences the detailed design of the engineered repository within it. The properties of the host rock, therefore, are among the important determinants of the total geologic environment of the repository. Several media have been studied and are under study to determine in a generic sense whether their properties are suitable for a repository host rock. These candidate media are discussed in Section 7 of this paper. At this point it is necessary only to identify some general properties that would seem desirable for a host rock.

Media that exhibit creep or plastic flow might be capable of sealing repository workings by flow without fracture propagation, or might self-heal in the event of fault-induced or subsidence-induced fracturing. Creep is observed in rock salt and to a lesser extent in some shales which, for example, can flow without fracturing at depths that are reasonable for repository construction using conventional mining techniques.

Another desirable characteristic of a host medium is that there should be minimal chemical reactions between the waste and the host rock to form compounds with high solubility or low melting points. Chemical reactions between rock and waste can change the source term for chemical transport because they change the leaching rate, alter the compositional and pressure gradients, increase the quantity of fluid available, or change the ionic strength of these fluids. An increase in the ionic strength decreases the sorptive capacity of the host rock for radionuclides and could increase the corrosion rate of containers. Chemical reactions that produce liquids or gases throughout the rock mass may also induce changes of acidity, density, or viscosity of the liquids or gases already present and thus reduce rock strength. Release of large quantities of gases or liquids throughout the rock mass could produce local pressures capable of hydraulic fracturing.

Media with high thermal diffusivity and conductivity and low thermal expansion over the range of repository temperatures are desirable. Such media could keep waste temperatures lower and undergo less mechanical deformation during heating and cooling.

Of course, the medium must be considered within the total system including waste form, mechanics of overlying rock strata, and hydrogeologic flow system. As already indicated, focusing attention on the medium to the exclusion of the other components of the waste isolaton system is inappropriate and misleading. A host rock need not exhibit all these properties nor necessarily have optimum values for any such properties that it does exhibit. The properties required of, or desirable for, any particular candidate rock mass depends on the other system characteristics for the particular site. Such a systems view leads to the possibility that a wider range of rock type might be of interest than has traditionally been considered. Besides salt, granite, basalt and shale, all of which are receiving considerable attention, anhydrite, tuffs and unsaturated alluvium might warrant consideration in some environments.

As pointed out by the National Academy of Sciences (25) and others (36), designing a waste repository constitutes a major challenge for rock mechanics both because of the thermal pulse and time frame during which repository behavior might influence radionuclide migration. The mechanical response of rock has relevance to problems of long term waste isolation to the extent that it would affect the transport characteristics of the geologic media in the vicinity of the repository site. Important parameters of this response are rock strength (ability to sustain differential stress) and ductility (ability to flow without fracture). Both strength and ductility are influenced by the presence of solutions and by increased temperature; in general, the strength is decreased and ductility is increased. Thermal expansion of rocks caused by increased temperature is a mechanical response of particular concern in the case of a radioactive waste repository. Aspects of rock mechanics relevant to problems of operating the repository have been addressed previously in the Section 3E of "The Operational Period". Considered here are those aspects concerned with near-field and far-field effects that may influence the security of waste isolation in the post-operational periods (37,38).

The principal mechanical effect from the waste will be the development in time of thermal stresses in the rock mass around the repository. Heating will generate compressive stresses in the immediate vicinity of the repository, with associated tensile stresses beyond the compression zone. The magnitude and extent of these stresses will depend on the layout and rate of heat generation of the canisters and will change with time. The specific effects of these stresses will depend on the relative magnitude of the pre-existing tectonic overburden stresses, and on the physical properties and other physical characteristics of the repository rock and associated geologic units. It is possible, for example, that the tensile stresses could reduce tectonic stresses sufficiently to produce slip on pre-existing fractures or joints in the rock mass. The tectonic stress in the region should be determined experimentally to allow the probability of such events to assessed. It is also possible that reduction of the net compression within the region of tensile stress would also increase the permeability, but new tension fractures are unlikely because the region will still be in a state of compression.

Fracturing can also result from increased fluid pressures induced by heating of the fluid or caused by pore volume reduction where thermal expansion of the rock begins to close fluid-filled voids. The compressional strength of all common rocks increases almost linearly with increasing effective confining pressure (and, therefore with increasing depth). Increased pore fluid pressure decreases the effective confining pressure and therefore decreases the strength of the rock, although any existing differential stress in the rock is not reduced. Because all permanent deformation other than compaction results from differential stress, increased pore pressure frequently results in fracture of the rock. This would, of course, contribute to increased permeability.

The extent of these and related effects must be evaluated by means of the science of rock mechanics, and will involve acquisition of data from both laboratory and in-situ mechanical testing in order to develop analytical models of the repository site. It should be emphasized, however, that models validated by such data for short-term (operational period) and near-field mechanical effects cannot be validated in the same manner for long-term and far-field effects because of the great length of time required for measurable effects to be observed at large distances away from the repository. Confidence in the ability of such models to predict far-field deformations over long periods of time will necessarily have to be based on the accuracy of short-term predictions and increased understanding of long term processes. Monitoring, for some period yet to be determined, will be useful to assure the accuracy (and safety) of the predictive models, and to provide an early warning system should the models prove to be unreliable.

As yet, little effort appears to have been devoted to modeling of the region away from the immediate vicinity of the repository -- emphasis has been on near-field deformations -- but, in principle, no reason exists to prevent this. Improved constitutive stress-strain relationships and better understanding of the mechanical response of layered media are needed for a refined analysis, but bounding limits could probably be determined with existing knowledge. The results would indicate the likely locations and magnitudes of displacements in the media, and those regions in which the rock strength might be exceeded. Far more difficult, and beyond the capability of the models, would be an estimation of the fracture density and other characteristics important to assessing changes in transport properties of the rocks. Such information would have to be obtained from combined analysis of data from modeling, experimental, and theoretical studies.

Because of the potentially serious consequences of thermal expansion, the different thermal loadings produced by reprocessed waste and fuel rods, respectively, are a matter for careful analysis. The capability currently exists to do this, and appropriate loadings can be determined once the relevant properties of the media have been specified.

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4D. Hydrogeologic Transport of Radionuclides

After a repository is fully loaded and sealed the most likely mechanism for the release of radionuclides to the biosphere is by their dissolution and transport in groundwater. Repositories located below the water table are expected to fill with groundwater. The rate of groundwater inflow will depend on the host rock permeability, the depth of the repository beneath the water table, the design of the shafts and boreholes, the effectiveness of shaft and borehole sealing techniques and, for salt, the rate of repository self-sealing as a result of plastic flow. After the repository and associated shafts are saturated, ground water flow through and in the immediate vicinity of the repository, will be influenced by a complex coupling of: (a) the thermal pulse; (b) the mechanical response of the host rock to repository construction and to the thermal pulse; and (c) the natural hydraulic gradients prevalent prior to repository construction. At a distance of several hundreds to several thousand feet from the repository ground water flow should be dominated by natural hydraulic gradients, gradients which have vertical as well as horizontal components.

The ability of the ground water to dissolve the wastes and transport the radionuclides from the repository depends on the following factors: (1) solubility of the waste form and of its container at repository temperatures; (2) the sorptive properties of the host rock at ambient and repository temperatures, and the sorptive properties of all other media along the groundwater flow path; (3) the chemical properties of the groundwater including its acidity, oxidation potential, ionic strength, complexing agents present, and chemical changes associated with emplaced waste; and (4) the rate of flow. Each of those factors is a function of still other parameters. For example, the flow rate is a function of permeability, porosity, and hydraulic gradient; and the rate of dissolving the waste is also a function of groundwater chemistry. The sorptive properties of rocks in turn are a complex function of: (1) the type of minerals comprising or lining the interstices and/or fractures through which groundwater moves; (2) the surface area of the sorptive minerals; (3) temperature; (4) acidity and other chemical properties of the groundwater; (5) the changing chemical composition of the groundwater as it moves along the flow path; and (6) the changing sorptive properties of the mineral surfaces due to breakdown of emplaced waste.

Once radionuclides are transferred to the ground water, e.g., as dissolved, complexed, or colloidal material, factors such as radioactive decay, dispersion, or the mixing of aquifer water with that from an adjacent stratum operate to determine the concentrations of radionuclides as they are transported towards points of potential human access. Briefly, prediction of the transport of radionuclides from a repository requires detailed knowledge of: the physical chemistry of the waste form; transient repository temperatures; and the three-dimensional distribution of the aquifer porosity, permeability, dispersivity, hydraulic gradient, sorptive characteristics, and water chemistry. These types of hydrogeologic and geochemical information are currently not fully available even for the best known aquifers and may require considerable effort to obtain at a repository site owing to the need to minimize disruption of the repository area by drilling.

Despite the anticipated data limitations, valuable estimates of the transport of radiocuclides by groundwater have been made by Burkholder et. al. (39), by Marsily et. al. (40) and others (41) using groundwater flow and mass transport models. By varying the boundary conditions and such generic input data as permeability, porosity, and sorption properties of geologic media for specific radionuclides, those models yield a measure of the relative importance of flow path length, flow velocity, and aquifer sorption characteristics as barriers to radionuclide transport. The models suggest that if a repository is sited where flow paths are sufficiently long, such as may be found in regional aquifer systems, then retention of radionuclides in the lithosphere for periods of thousands of years may be considered likely. Site specific analyses would require a firm knowledge of the vertical components of groundwater flow, components which could transport radionuclides to relatively shallow aquifers from which well water might be withdrawn at some time in the future (see Section 5). Such knowledge can be obtained by standard hydrogeologic techniques for rocks of moderate to high permeability but will require special techniques for less permeable rocks.

Not all of the types of data outlined above are needed in equal detail. For example, if the flow path from a repository to a point of groundwater discharge is a few kilometers or less, and if flow is chiefly via fractures, the solubility of the waste form and canister and the sorptive characteristics of the aquifer(s) would be the only major barriers to radionuclide transport. On the other hand, in regions where flow paths are on the order of 50 kilometers or more, and when flow is chiefly through rock interstices, the solubility of the waste might be of lesser importance. Similarly, despite the acknowledged difficulties of characterizing, and hence of modeling, the flow of groundwater through fractured media, such characterization may not be necessary in all hydrogeologic environments. For example, characterization of flow of water through fractured shale may not be required if the ground waters are datable (say, by carbon-14) and are older than 30,000 years in the vicinity of the repository (Methods for dating groundwaters older than several tens of thousands of years are presently being investigated by several universities through the sponsorship of the Office of Waste Isolation and DOE).

It is almost axiomatic to state that groundwater flow and mass transport models must be employed to help identify the factors affecting the radionuclide transport that are critical at each proposed site for given time frames. Current modeling efforts now recognize that: (1) results should state error limits and should show possible ranges of the effects; and (2) input data and boundary conditions must reflect appropriate hydrogeologic and geochemical information. Although a considerable body of data exists on the sorptive characteristics of various media for selected radionuclides, these extensive measurements have not been made under conditions that are characteristic of the temperature, pressure, or chemical complexity of a selected repository and of the deep aquifer environment; including modifications resulting from the chemical breakdown of emplaced canisters of waste. Hence the utility of existing data is limited. Similarly, boundary conditions described as "conservative" by a modeler may prove highly permissive to another scientist. A range of boundary conditions must be investigated in generic modeling, both to improve our understanding of the importance of repository design parameters and to increase the likelihood that generic modeling experience will be applicable to proposed sites.

The analyses of radionuclide migration cited on the preceeding pages generally assume that groundwater flow will be controlled only by the natural hydraulic gradients. However, as stated in the opening paragraph of this section, ground water flow in the immediate vicinity of the repository will also be influenced by the thermal pulse and the mechanical response of the host rocks to repository construction as well as to the thermal pulse. Detailed studies of such flow are also important. For example, water-flow within the repository itself may be of major importance if geochemical redistribution of the waste and container materials might result in new chemical forms with changed sorption characteristics, zones of high concentration of certain elements, and altered time release rates of radioactivity. Additionally, it has been postulated (42) that in low permeability media such as shale or salt, inflow of water into a repository might result in hydrofracturing of the repository rocks due due to thermal expansion of the water. Whether this is a realistic scenario and the extent to which the postulated hydrofracturing might extend from the repository into overlying aquifers is under appraisal (42) using ground water flow models developed for analyses of geothermal reservoirs.

As a third example, in areas with natural vertical components of ground water flow, shafts and (repository-related) drill holes constitute potential short circuits of natural ground water flow; they merit serious study.*

* Despite efforts to seal shafts and boreholes, and the fractures induced during their emplacement, they remain potentially important pathways for radionuclide release from a repository. This important matter is under study by OWI. Consensus does not now exist that borehole sealing materials and technology, currently anticipated to be special concretes, will provide an adequate seal even over time frames of decades. A field demonstration is needed on borehole and shaft sealing and on the interaction of the sealant with the host rock; care must be taken to assure that placement of the sealant does not itself induce microfracturing.

5. LONG-TERM RISK ASSESSMENT

Risk assessment of a nuclear repository involves two types of predictions: probabilities of events or chains of events occurring that lead to the release of radionuclides to the biosphere, and consequences of these releases. "Risk" is the probability-consequence pair and risk assessment must include an estimate of both. Within 3 to 5 years a risk methodology should be available that will permit estimates of repository risks and that can provide a partial basis for judging the acceptability of options for radioactive waste disposal. Given the nature of the uncertainties associated with repository storage, however, complete risk assessment may never be possible. But risk assessment methodology can bound the uncertainties, structure what is known and to some extent identify what is unknown, identify important mechanisms for release, and quantitatively estimate how uncertainties combine to yield risks. A risk assessment should not be intentionally conservative. Rather, it should attempt to be realistic and, to the extent possible, should indicate the distribution of the risk that derives from uncertainty in the input parameters and in the model itself.

The inability to do a precise risk assessment should not dissuade one from attempting it. The insights and information gained from attempting a complete and comprehensive risk assessment could be more valuable than the resulting estimates of risk. For example, the results of an attempted assessment should enable one to identify those characteristics and properties of the system under study that can contribute significantly to the public risk. This information would permit one to focus better on further research and investigation that could significantly improve the safety of the system.

5A. Methodology of Risk Assessment

Among the most difficult aspects of risk assessment is ascertaining that all dominant sources of risk or pathways of radioactive wastes to the human environment have been identified and that these are accommodated within the existing structure of models developed for the assessment. These models are necessarily complex and it is difficult to validate them, inasmuch as very limited data exist for radionuclide transport in natural systems or for the effects of disruptive events on such systems. Confidence in the models can be developed by comparing their output with parts of natural systems for which data exist (e.g., groundwater flow and discharge) and by comparing the output from different models that have independently analyzed a hypothetical but realistic situation.

Uncertainties associated with the results of risk assessment are of four types. First is the uncertainty caused by lack of data. Presumably this type of uncertainty can be reduced but not totally eliminated by continued research and analysis. Detailed site exploration will, of course, provide data for use in the site-specific risk assessment. Second, uncertainty results from lack of experience. This type of uncertainty involves identification of mechanisms and scenarios; it is only partially reducible by continued research. Third, uncertainty exists due to natural variations in physical properties. In principle, this uncertainty is reducible with extensive field exploration and analysis, at particular sites, but practical limits are imposed by cost, time, and the need to protect the integrity of the site. Fourth, uncertainty results from an inability to predict the future of long-term geological and climatic processes, and of social evolution. These uncertainties are predominantly not reducible, but can be estimated by careful selection of appropriate scenarios. The uncertainties from the sources mentioned above are neither additive nor of equal significance; sensitivity analyses can be used to determine their relative importance and contribution to the overall uncertainty of risk estimates.

Possibly the most important aspect of risk assessment of radioactive waste disposal is to understand how the uncertainties mentioned above enter into the calculation of risk. Detailed modeling of the processes by which waste could escape from a the repository, move to the biosphere and, ultimately, to humans is required if the effects of these uncertainties, both on the likelihood of release and on the consequences, are to be evaluated.

An important limitation to the ability to assess risk lies in associating probabilities with geological processes, both for long-term events and for those of immediate engineering interest. Development of probabilistic models in geology is recent, but advancement of the techniques is proceeding rapidly. For the present, the inability to model geological and hydrological processes is a serious limitation to risk assessment. However, continued work over the next five years may yield sufficient progress that at least short and immediate term predictions can be better made. Comprehensive probabilistic predictions for the long-term, and even detailed probabilistic predictions for short and intermediate terms seem farther off. It may be that "conditional" risks will have to be calculated -- i.e., risks that would exist if the assumption made in the analysis about future events (climatic factors, land use, etc.), do hold.

Major current work that could be classified as risk assessment of nuclear wastes in deep geologic formations is being performed by Sandia Laboratories and Lawrence Livermore Laboratories for the Nuclear Regulatory Commission, by Arthur D. Little, Inc. for the Environmental Protection Agency, and by Battelle Pacific Northwest Laboratory for the Department of Energy. These analyses are for generic (i.e., non-site specific) repositories, and generally are for bedded salt. Generic analysis is not applicable to particular sites, but does permit development and exercise of a methodology that can be applied at the appropriate time to specific sites selected for study. Several years of activity have led to a consensus that the three most important modes of potential release are: transport by groundwater, catastrophic release to air (e.g., as a result of meteorite impact), and removal by man (e.g., from mineral exploration). Release scenarios that involve migration in groundwater flow have received the most attention to date because dissolution and transport in groundwater is believed to be the most likely mechanism for transfer of radionuclides back to the human environment.

5B. Local Release from the Repository and Movement Through the Subsurface.

It is expected that only areas with a long history of geologic stability will be considered as potential candidates for waste repositories. Certainly, past stability is a reasonable requirement for repository site selection. However, a history of geologic stability is not sufficient to assure future stability for the area with or without the development of a repository. The development of a waste repository could constitute a significant alteration of the local stress field and no amount of back-filling or sealing of shafts will restore the area completely to its original conditions. Once a repository is filled and sealed, the area containing it might evolve differently than if the repository had not been placed there. Release modes that need to be considered therefore include those that are self-induced as well as those which could occur independently of the presence of the repository.

Analyses of local releases have considered such factors as waste-rock interactions and thermomechanical behavior in the near field. Those processes initiated by the presence of the repository constitute one category of disruptive events. In addition, external events independent of the presence of the repository--such as seismic activity, magma intrusion, or meteorite impact--may enhance processes that directly or indirectly lead to release of the waste.

One assumption commonly made in assessments is that immediately upon closure of the repository, or at some postulated time after closure, radionuclides in the wastes are completely dissolved in circulating groundwater. The time required for their movement to the environment is then estimated by assuming that the radionuclides move through overlying formations along specified paths to the surface. The pathways may be arbitrarily defined, or determined by sophisticated ground water transport modeling. Such an assumption is conservative, because it overestimates the rate of release from the source. To the extent that radionuclides are prevented from going into solution, the release rates are proportionately reduced.

If waste is locally released from the repository, it must move through surrounding formations before entering the human environment. This movement will be substantially controlled by the hydrogeologic regime, inasmuch as the groundwater flow field largely defines the potential for movement of dissolved radionuclides. The flow field and potential pathways for dissolved waste to reach the surface are difficult to predict for times in the future, but appropriate bounds can be placed on them. For the near term (e.g., first few hundred years) the pathways depend on the present distribution of permeabilities (including fractures), the hydraulic gradients, the thermal field, geological inhomogeneities, unplugged boreholes, and other phenomena either resulting from the creation of the repository or exogenous to it. In the distant future (e.g., beyond a few hundred years) the pathways depend also on climatologic and geologic changes.

Analyses now in progress treat hypothetical generic profiles, modeled as Darcy flow regimes. Fracturing and faulting are modeled as short circuits in this flow. Parametric uncertainty is treated through sensitivity studies, but at present not by assigning probability distributions to the input. The results of these analyses are rates of release to the surface for given source terms and flow conditions as a function of time. Future risk assessment will have to address probabilistic description of flow conditions and changes in those conditions, and the possibility of non-Darcy flow regimes caused by convection currents or other processes.

5C. Movement of Radionuclides Through the Environment and Uptake by Humans.

If radionuclides become dissolved in circulating ground water, they could enter the human environment in a variety of ways, such as discharge of ground water to surface water (e.g., springs, rivers, etc.) or direct withdrawal of contaminated well water by humans, or indirectly (i.e., through food). The subsequent movement of radionuclides through the environment, their accumulation in soil, air, and water and their eventual uptake by humans has received considerable attention by the IAEA (62).

Analysis of environmental impact and human uptake of radionuclides could add as much, or even more, uncertainty to the evaluation of risk as that associated with release of wastes from the repository and their movement through the subsurface. Surface features, particularly those which may be influenced by humans such as river water flow rates, creation of lakes and dams, and changes in water runoff patterns, can be expected to change more rapidly than subsurface features, and are considerably less predictable.

Factors directly related to future human actions play a prominent role in determining the effects on humans of released nuclear wastes. One of the more important uncertainties is population density in areas that could potentially become contaminated. Population density could vary from zero to far higher than in the now most densely populated cities. Furthermore, factors related to water usage are important. If agricultural areas should become contaminated, irrigation from a contaminated river or contaminated ground water would significantly increase the contamination of food crops and thus increase the human uptake of radionuclides through food chains. Nevertheless, as with certain geologic and climatic factors, bounds can be placed on the ranges of demographic and other human factors. Because answers to questions regarding human actions are unknowable, consistent assumptions must be made so that comparison of relative risk is possible.

5D. Accuracy, Gaps of Knowledge, and Future Development of Risk Assessment.

The accuracy of risk assessment is not limited by the methodologies of risk analysis but by the uncertainties associated with geologic and hydrogeologic processes and future human activity. The construction of scenarios leading to the release of waste from a repository is generally agreed to be an important issue in evaluating those risks.

Important knowledge gaps for risk assessment include:

- The ability to incorporate the variability of physical and chemical properties in geologic and ground water flow modeling.
- Identification of important mechanisms of waste-host rock interaction and quantification of levels of uncertainty in those mechanisms.
- The ability to characterize the natural variability of repository sites by means of exploration programs.
- The ability to predict long-term geological, hydrological, and social changes.

In these four areas, improvements in knowledge does not necessarily mean reduction of uncertainty. Uncertainties associated with the first three of these areas are potentially reducible to numbers. Continued or accelerated work should significantly improve our abilities to deal with the problems, particularly in better understood waste emplacement media. Uncertainties associated with the fourth area (long-term predictions) may not be quantifiable, but further work directed at developing a way of handling long-term predictions may provide satisfactory alternatives to explicit quantification.

6. SITE SELECTION AND SITE CHARACTERIZATION

The establishment of a site for geologic disposal of nuclear wastes must necessarily proceed in a certain orderly sequence. First, the properties of a site which make it desirable for such disposal must be specified, at least broadly. Second, some candidate regions which may have such properties must be selected. Third, these regions must be studied in some greater detail to determine some candidate sites of lesser geographical extent for even more detailed investigation. The process to this stage can be broadly denoted as "site selection", and the sequence outlined above depends strictly on scientific or technical information.

The site selection process can also take on a different character. Sites can be selected for detailed investigation based on availabiligy, ease of access, or simply ownership by appropriate bodies (e.g., DOE). These sites may then be studied in more detail to determine their suitability for a repository. In either case (selection by technical/scientific culling or selection according to other factors) the investigations of the site which lead to its designation as a repository include much the same studies and factors.

In the discussion that follows, a sequence of purely technical and scientific decisions is assumed. All of the information required for the decision is needed no matter which of the selection processes is followed.

The identification of candidate sites by scientific culling should ideally begin with regional studies with a broad program that would include geologic, hydrologic, geochemical, and geophysical studies needed to confirm, or disconfirm, the presence of multiple natural barriers within the geology and regional ground water flow systems. Involved here would be geologic mapping, test drilling, and regional geophysics. Areas of perhaps 2,000 to 10,000 square miles would be sought that have favorable hydrologic and geologic characteristics. A subsequent more detailed exploration program within such large areas would identify 40 to 400 square mile blocks that appear particularly favorable as potential repository sites. Finally, candidate sites would be selected with areal extents of perhaps 10 square miles.

At each step in this process, appropriate technical criteria will be required to guide the work and facilitate judgments of suitability. Criteria are under development by the Nuclear Regulatory Commission (44), by the Department of Energy (46), and others (43, 45, 47). Such criteria are based on the notion that we must limit, to the extent possible, the likelihood of radioactive wastes being released from the repository to the human environment, and the consequences of the release. Therefore, the criteria should address systematically the significant features of the repository and its environment that bear on its ability to isolate the wastes for adequate periods of time.

Although satisfaction of appropriate technical criteria is essential at each stage of the work, other factors also are relevant to the site selection process, and could dominate. Among these are ease and cost of access, distance from other societal activities, and societal acceptance of the location as a candidate repository site. Large areas of the country may be ruled out by these latter nongeologic factors, totally independent of their possible attractiveness from a geologic perspective. Other areas may be highly favored by the non-geologic factors. Indeed, the practical aspects of gaining access to land for reconnaissance and exploration may impose severe restructions on the areas available for consideration at least over the near term

If (as seems likely now) the criteria for suitability of a site cannot be specified in great detail because of the complexity of the geologic settings, it is possible that the initial selection will need be done mainly on the non-technical factors. Whether a site is selected this way or by a strictly scientific search and culling it will need be examined in detail and compared against the underlying radiological safety criteria.

Once a potential site is identified, an intensive exploration program will be required to characterize it. The predictions and hypotheses made during the proceding more general reconnaissance program can be verified or disproved. Detailed geophysical studies and some coring will be required as part of a lengthy program. Among the most important data to be gathered are details of the local ground water hydrology with respect to the regional flow system, the sorptive characteristics of the rocks along the flow paths; the geochemical and thermal properties, the fracture patterns and stress field of the candidate host rock and its surrounding rock structures; and the resource potential of the site, if any. The latter point is important both because the presence of resources in the area might provide incentive for human penetration of the repository at some future time after memory of the repository's existence has disappeared and because competition with possible near term resource exploration claims might argue against the site's use for a repository. A site-specific safety assessment, of course, will also be required to compare the consequences predicted over a range of scenarios with programmatic and regulatory standards.

The comparison of the information gained by the site characterization with the criteria for site suitability is a task of some magnitude and some importance. Only with an ongoing and intense program for the evaluation of the forthcoming information can the data be shown to be satisfying the needs of the criteria and the decision process. Each site, of course, will have a unique set of features and characteristics. Only the ability of the total system to guarantee containment is of interest, however. Considerable flexibility is therefore required in specifying and applying site suitability criteria. But caution must be exercised to prevent the detailed criteria from being adjusted simply to accommodate the actual features of a particular site under study. This care can best be taken in the formulation of the criteria.

Although, in principle, the data required for site characterization can be acquired by employing standard geophysical, geochemical and hydrological exploration techniques, in practice important limitations exist.

Geophysical techniques are limited in their ability to obtain information at depth and to detect and identify small anomalies in the rock structure. The frequency and hydraulic interconnection of fractures are particularly difficult to determine either by geophysics or by permeability tests from a limited number of boreholes. The ability to extrapolate from the rock immediately surrounding such holes to the large scale characteristics of a site is limited. As already discussed, more boreholes could be drilled. Under some circumstances this may be undesirable.

It is prudent, therefore, to consider the trade-off between the need to obtain sufficient information to characterize a site and the need to maintain its natural integrity. Uncertainties will always remain and we must be careful not to demand more data that can be obtained or than is really needed. The degree of detailed information required of a particular site can, to some extent, be determined by conducting sensitivity analysis in the site specific safety assessment work. Fortunately, current techniques do seem to permit the acquisition of sufficient data to characterize a site satisfactorily from an overall systems perspective. New geophysical techniques including high-resolution seismic and acoustic, short-pulse radar and continuous wave interferometry methods now under development will contribute to greater understanding of a potential site.

Not everything will be known, however, before a shaft is sunk and horizontal tunneling can be done. Important data will be continuously collected during the site characterization study during the various phases of the repository construction such as shaft sinking, drift excavation, and during operation of the repository.

It is important to point out that to date most modeling and on-location experimentation and measurements have been done for the purpose of generally characterizing media. Such work is very useful but must be considered primarily as having generic value by developing methodology development and heightening awareness of important questions that must ultimately be applied to specific sites. The importance of examining actual potential sites cannot be overestimated. Moreover, given the long time required to do the necessary work, there would seem to be advantages in conducting detailed site characterization studies at a number of sites simultaneously.

7. CANDIDATE MEDIA

Information available and work underway on candidate host rocks will be summarized in this section. There is, of course, a range in the physical, chemical, and mechanical properties of any rock type both at any given site and at different sites. The rather general tone of the subsequent discussion of geologic media is not intended to obscure the fact that these variations occur and must be taken into account and that generic data about a media, though a necessary first step, are no substitute for the required detailed site investigations.

7A. Rock Salt.

Rock salt, of either the bedded or dome variety, has received the bulk of the attention over the past decades.
The original NAS-NRC Committee (48) recommended salt because of its thermal and physical properties, and its very existence for 200 million years or more which demonstrated its isolation from aquifers and the stability of the geologic formations in which the salt is located. Another desirable feature of many bedded salt basins, a result of their evaporite origin and subsequent tectonic history, is their relatively simple structure and predictable stratigraphy. It is often possible to establish geologic structure and predict lithology of the formations over a wide area with relative ease. Because of the early start on investigations of salt considerable data are available on the properties of salt and its response to thermal loading (18). Extensive laboratory testing is underway at Sandia (49) and by OWI (15) and in-situ heater

experiments with control of fluid pressures are being conducted at Asse, Germany (50) and Avery Island, LA. (15). Thermal experiments are planned for a potash mine near the proposed WIPP site in FY 1979. Intrinsically desirable properties of salt include uniformly low permeability, high thermal conductivity, abundant availability in thick masses, and plasticity that enables fractures to self heal at feasible repository depths.

Several questions have been raised concerning specific phenomena that might affect the ability of salt to afford the permanence of isolation of waste required in a repository; some and possibly all may be accommodated by appropriate engineering or operational approaches. All the problems identified in the subsequent discussion are receiving intensive study domestically and abroad, and it is expected that within the next 5 years that the relative importance of these problems will be established and many will be resolved. The R&D facility associated with WIPP (a proposed transuranic waste repository) will provide experimental in situ verification of these results.

One potential problem is associated with the plasticity of salt and its impact on long-term retrievability. Salt is more plastic at any given temperature than most other rock types. Two specific effects must be considered: the first is the closure of the hole in which the waste is placed and the second is the closure of the storage rooms. Engineering approaches (such as controlling the temperatures in the salt, or use of mechanical restraints) can be employed to mitigate such effects. Each of these approaches along with numerous others, has been considered and specific practical approaches have been defined to accommodate the situation. Retrievability in a salt formation could be maintained, The cost would be determined in part by the length of time retrievability is required.

Since water can lower the mechanical strength of salt, its presence and variable concentration could be a problem. The mean water content in salt is low (usually less than 1 percent), but local variations over wide ranges occur within salt masses. The water content tends to be lowest in the salt domes along the Gulf Coast where the deformation and flow process which formed the domes seem to have kneaded the water from the salt. Bedded salt strata such as those in New Mexico, Utah, mid-Continental and Eastern USA are generally more variable than dome salts in their chemical composition and mineralogy. They commonly contain complex hydrous halides, sulfates, and larger variations in contents of free and combined water. More detailed mineralogical characterization may be required for sites in bedded salt than in domal salt.

The high sensitivity of salt to solution processes requires that sufficient knowledge of regional and site hydrogeology be obtained before a repository is operated, and that some assurance about possible future groundwater flow regimes also be obtained. At present such understanding depends in part on our limited ability to predict tectonic stability and future climate, both of which need improvement in levels of effort and methods of study. However, only limited increased capability is probable over the next decade, although programs are underway at several universities, the USGS, and other organizations.

Another potential problem is related to the interstratification of the non-halite members and shale beds associated with bedded salt formations that result in higher average water content, and a broader range in chemical composition and mineralogy. It has been postulated that the thin interbeds of shale, anhydrite or dolomite could increase lateral flow rates. However, it is now clear that these thin interbeds need not be active conduits for water flow since the effects of dissolution can be detected and the presence of flowing water can be measured. (For example, at WIPP such interbeds are known to exist and the cores taken indicate no such past flow.) The interbeds might conceivably become a conduit if they were connected to an aquifer in the future or if the repository were penetrated by water. In general, however, these interbedded layers have low permeability. The consequences of flow through the pores of the interbeds can be estimated by means of existing calculational techniques and are likely to be less significant than other plausible failure paths.

The solubility of rock salt in water is two orders of magnitude greater than that of any other candidate medium. In the event that construction, operation, or loss of integrity over geologic time causes water to flow through a salt repository, dissolution could cause release of the waste. Although the principal channels for flow in the salt might be along shale interbeds or fractures that may have concentrated clay minerals, the sorptive capacity of these channels will be diminished by the presence of solutions of high ionic strength. Similarly, the sorptive capacity of other geologic materials along the flow path will be decreasd by the high salt concentrations.

Another potential problem is the presence of major heterogenieties in the salt formation such as structural features that result from flow of salt or large brine or high pressure gas pockets which cannot be detected until encountered. (Gas pockets are not limited to salt formations - they are characteristic of many geologic media and formations). These defects may not represent a threat to the long-term integrity of the repository, but they could represent a threat to the safety of those who are constructing and operating the facility. For example, mining into a large brine pocket which is not connected to any source of water could harm the miners but should not threaten the capability of the repository to perform its isolation function.

Special geophysical methods are being developed for characterizing geologic formations which have a high electrical resistivity such as salt. These techniques have been used successfully in a few cases but only limited applications have been achieved. A major national program (at Sandia, LLL, and USGS) on instrument development is underway to increase the range (up to a kilometer) and resolution (down to tens of centimeters) of these methods which offer the potential to locate trapped brine, disturbed rock structures, variations in water content, etc., in advance of mining.

The thermal expansion of salt is almost three times that of other candidate media. Thermal expansion is a significant physical property in that it is the major design parameter controlling the vertical uplift resulting from the increase in temperature in the repository volume and the surrounding geologic media. A major impact of the thermally induced uplift is the flexural deformation of the overlying strata which has protected the salt formation from the groundwater above. In this area the rock mechanics analysis is adequate to predict rock stresses and strains for a particular site. However, the capacity of these stresses to induce fractures must be determined for each site and coupled with fluid flow phenomena. With prudent design matrices that limit the temperature increase, fractures within the overlying strata can be minimized.

Another issue with rock salt is related to the physical-chemical behavior of the small brine and bittern (brines containing high concentrations of magnesium and calcium chlorides) inclusions which are present within and at the boundaries of crystals of bedded salt (51,52). Experiments (18) show that in salt these brine inclusions will migrate up a thermal gradient toward the heat source. The pressure in the brine inclusions increases when they are heated. If the temperature near the waste canisters is high enough, the fluid pressure in the inclusions may exceed the strength of the salt and cause it to flow or even to decrepitate, releasing the fluids and decreasing the thermal conductivity of the salt. It is expected that these brines will reach the holes in which the waste is placed. The nature of the effects that will take place when and if the brine arrives in volume is not determined, but are likely to be deleterious.

Several hypotheses with respect to the potential reactions that may take place have been proposed. One hypothesis proposes that substantial quantities of brine will be drawn from the surrounding salt, diminishing its moisture content. The brine phase concentration in the salt in a small volume surrounding the waste will increase causing the mechanical strength to be reduced. The strength of salt which has been depleted in brine should increase. The brines are expected to fill the void space around the waste canister so that corrosive liquids that have low pH values (by hydrolysis at repository temperatures) will be in contact with the waste canister. Under these conditions it is expected that these brines, with high concentration of dissolved salts, will attack waste canisters and subsequently the waste. However, the rates and extent of such reactions are still unknown.

Another hypothesis states that elements from the containers and waste added to the brines will increase the total amount of dissolved salts and to some extent will increase the amount of brine present at constant water content. An alternative hypothesis states that the point must be considered as to how fast glass or spent fuel will dissolve in a solution of saturated brine. It does not take into account the fact that, as the metallic canister corrodes to form sulfides, oxides, chlorides, and hydroxide corrosion products, the amount of water will decrease by its reaction to form hydrogen, oxides and hydroxides. The heat generation rate is maximum when waste is first emplaced, and after an initial heat-up period, the temperature will decrease, reducing the potential for bringing water to the wastes. As the temperature decreases with time and as the quantity of water decreases due to corrosion interactions, dissolved salts may precipitate, minimizing the rate at which the high level waste could be attacked. Specific steps to reduce the potential for corrosive brines contacting the waste and canister must be taken. Materials can be placed in the vicinity of the bore hole specifically selected on the basis of their ability to react with brines to form solid corrosion products, thereby reducing the detrimental effects of high brine content on the mechanical properties of salt.

The chemical reactions which will take place in the vicinity of the waste, accelerated by elevated temperatures and high pressures, are complex and far from clear. Complicating the picture further is the unknown but certain effect of the radiation on these chemical reactions. Gaps in our knowledge here need to be filled by laboratory data and in-situ data, if possible.

Often design features may be devised that can resolve potential problems. For example, it has been proposed that after a repository closure brines might attack the seals of bore holes and shafts. If the shafts and bore holes are located at a distance and down gradient from the heat source, it is not clear that brines would collect in these areas and pose any threat to the seal.

In bedded salt, large diameter (the order of 1000 ft) vertical, and possibly permeable structures, known as breccia pipes, occur. They are formed by a solution mechanism but the nature of the formation process is not understood. Such pipes exist in many salt basins and they extend vertically through several of the geologic strata of both saline and non-saline origin. These pipes, if located near a repository, and if permeable, could provide a shortened path to the biosphere. If such a feature is in existence its presence can be detected with existing geophysical and geologic exploration and evaluation techniques. The existence of a permeable breccia pipe in an area would provide the necessary reason not to construct a repository in the vicinity. The main question concerning the understanding of the formation of breccia pipes is to assure that one could not form in the vicinity of a repository after the repository was closed. If it is shown that breccia pipe formation is associated with geologic processes which are no longer active in a given area then they will not represent any threat to a repository in salt. Sandia has underway an extensive program to provide an answer to this question and should be able to resolve the question within the next few years.

In summary, salt is best understood of all the geologic media in many respects and it offers advantages in thermal properties and plasticity. With conservative engineering salt may be an acceptable repository medium. However, salt is soluble and it does not provide the sorptive qualities of other rock types nor is it benign to interactions with the waste and container. All of these could be troublesome in the event of breachment of repository integrity.

7B. Anhydrite (Calcium Sulfate)

Anhydrite is not yet a candidate repository host rock in this country, though it has been considered in Switzerland. Anhydrite is available in thick, homogeneous masses of low permeability in many areas of the U.S. west of the Mississippi River. Anhydrite has a thermal conductivity as high as rock salt, but expands only one-third as much at the same temperatures. Anhydrite is stable to very high temperatures, and, in general, contains little free water. The solubility of anhydrite in either weak or strong brines, decreases as temperature is increased up to 230 degrees C, a unusual phenomenon. This means that fluids cannot migrate up the thermal gradient into the repository by solution-dissolution mechanisms. From the few data available (Sandia) anhydrite seems to have significantly higher sorptive capacity than the salt strata with which anhydrite commonly is associated. Anhydrite is more difficult to mine than rock salt. It is also brittle and fractures rather than flows at reasonably repository temperatures and pressures, and the fractures that develop do not self-heal.

Anhydrite hydrates to gypsum in the presence of water of low ionic strength, but not with water of high ionic strength. The hydration of anhydrite is accompanied by swelling of 62 percent by volume. Fresh water that reached anhydrite would be partly fixed as gypsum, and the resultant expansion could possibly prevent further flow or could even cause fracturing.

In 1979, the USGS proposes to initiate studies of anhydrite to evaluate its potential as a repository host rock.

Anhydrite occurs in the same geohydrologic environment as salt, and is usually interbedded with salt, shale, and dolomite. These bedded sections tend to have long flow paths for liquids that escape from individual beds and may offer a considerable range of sorptive formations along the flow paths. Though much less soluble than rock salt, anhydrite is still a soluble rock. The hydrologic regime is characterized by horizontal flows along bedding planes, but some channeling (cavern formation) has been observed in anhydrite similar to that of limestone and gypsum.

7C. Granite and other Crystalline Rocks

Granite and other crystalline igneous rocks and metamorphic rocks, such as gneiss, have been proposed as potential geologic media for a repository because they occur in very large and relatively homogeneous masses. Crystalline rocks such as granite are attractive because of their strength and structural stability. The water content of the rock is low and largely in fractures. Granite has good sorptive properties and the ionic strength of water in such formations is usually low, minimizing corrosion rates and the effects on sorptive characteristics. Because of these favorable natural conditions it has been estimated that the waste containers in such conditions might maintain their integrity over many hundreds of years (53).

While the U.S. has placed major emphasis on salt, other countries with abundant granite such as Sweden (53) Canada (20) and the United Kingdom (54) have been evaluating it as a repository medium. Secondary barriers within granite to enhance the retention of radioactive nuclides within the repository are also being studied. One technique proposed by the Swedish Power Board is backfilling the volume around the waste canister with a sorptive material mixture (quartz and smectite) to buffer the ionic strength and acidity of the water and minimize corrosive attack on the canister while still retaining high sorption in the mineral mixture. While this approach has been considered a possible approach to the retention of radioactive nuclides in a repository, the validity of this proposal has not yet been demonstrated.

The groundwater flow paths through crystalline rocks are normally, but not always, shorter than those in bedded strata such as shale. This path length depends, of course, on the geohydrologic setting. Crystalline rocks commonly occur in geohydrological environments that have experienced complex tectonic histories during which the rocks were metamorphosed and thermally disrupted several times. Changes in rock properties probably occurred during these events. Rock properties may have been homogenized by pervasive events or may be quite variable from place to place and difficult to ascertain adequately for repository design. Geohydrological characterization of such crystalline rock terrains will be difficult.

Granites are usually fractured; consequently the permeability of the rock mass depends upon flow through a network of fractures rather than flow through pores. The permeability of the "rock mass" is much less than that of the individual fractures. However, flow through a fracture depends on the size of the aperture which to a large extent is controlled by the normal stresses acting across the fracture. Since these stresses increase with depth, the permeability of fractured rock usually decreases with depth. Development of a model for fracture flow is a difficult technical problem that is receiving considerable attention. The use of granite for a repository, therefore, may require sites at depths at least as deep as 500 meters below the surface where the fracture permeability will be sufficiently low so that, considered from a conservative position, it may not represent a threat. Another possible approach would be to inject a thin grout into the fractures to reduce permeability.

7D. Shale and Related Rock Types

Shale and related rock types, here collectively called shale, have been identified as geologic media which have a number of attributes which make them attractive for the isolation of nuclear waste. These properties include low permeability, plastic flow under lithostatic load, good sorptive characteristics and low solubility in water. Shale is abundant in thick masses throughout the Midwestern and Western United States. However shale is a generic name for geologic materials which vary widely in character and composition. The suitability of shale will have to be determined on a case by case basis.

The response to a repository of shale formations will be similar to that of granite and other hard rock formations. After the repository is closed, water will fill all voids and the waste canisters will be in intimate contact with the water. Repositories will have to be designed with this characteristic in mind with appropriate provisions made to minimize the potential for the transport of radionuclides. While the filling of a repository with water may be cause for concern, several factors must be considered. If the residence time of the water is long, or the solubility of the radionuclides in the water is small, and if the sorptive properties of the shale are high, then the potential for the radionuclides reentering the biosphere is small. Two reasons why shale is considered attractive is that it has high sorptive characteristics for radionuclides and it has low interstitial and generally low fracture permeability, limiting the ability of water to flow through the formations. The composition of the water in shale varies widely, and in some areas is quite saline.

While shale offers many positive characteristics, a feature which may limit the usefulness of some varieties as a repository medium is thermally induced mineralogical changes which occur at temperatures as low as 100 degrees C in those varieties such as expandable clays. It may be postulated that the partial dehydration of some of the constituent clay minerals as well as heating pore water will increase the fluid pressure on the rock and, thus, drastically change the stress deformation properties of the rock. The visco-elastic properties of shale, which are temperature dependent, would also be affected but little data has been available to estimate the effects (10) At temperatures above 100 degrees C mineralogical transformations take place at rates that increase the permeability and porosity of shales during typical repository containment periods and thus affect the radionuclide transport rates. Attempts have been made to perform single preliminary field heating tests in two shaly rocks (Conasauga shale, TN; Eleana argillite, NV) to determine appropriate experimental methods to measure the temperature sensitivity of shale and to obtain generic data for the initial and post-heating states of these rocks. Experimental study of waste-shale-fluid interactions are underway at the Pennsylvania State University. It is probable that more than five years of intensive effort will be required to obtain adequate data to develop generic knowledge of the maximum temperature that shale repositories can sustain.

The concern of the potential deterioration in shale, associated with temperatures over 100 degrees C in large volumes of rock, cannot be evaluated at this time. If one considers profiles for various areas and at various times the volume of shale that would be above 100 degrees C in temperature, assuming a waste canister temperature of 250 degrees C, is quite small in comparison to the repository volume. However, the effects of heat on ground water in the repository after closure, for example, the potential for hydrofracturing needs careful examination.

The sorptive capacities of shale (55, 56) are generally high for most radionuclides and they are not significantly reduced at elevated temperatures above 100 degrees C. Moreover, the diminution of the sorptive properties will not be a significant factor if the repository is designed so that only a small fraction of the shale in the repository will experience temperatures greater than 100 degrees C. Even with the knowledge of the sorption coefficient, forecasting the transport of radionuclides in shale is considered to be a difficult problem. Because of the low permeability of the shale, transport is expected to occur principally by fracture flow, and there is not yet an adequate theory for accurate forecasting of such flow. Although there are several active research and development programs with respect to this problem, five years or more may be required to develop an adequate model.

A characteristic of shale which must be viewed as a potential drawback is the difficulties associated with mining and keeping the tunnels open. Inhomogenities in shale which significantly affect its structural characteristics are difficult to identify in advance of mining. An example of such effects can be found in the Eleana argillite at the Nevada Test Site (NTS). Based upon core holes there, it is estimated that about 20 percent of the volume of the shale is a highly plastic material which readily deforms to close unconstrained openings. A detailed engineering study (57) of the requirements to mine and maintain the opening would require extensive rock bolting and sets, and and would add approximately 25 percent to the total cost of mining tunnels at the NTS.

7E. Flood Basalt

Flood basalt is a candidate medium at the Hanford site, WA, where it occurs in a thick section near the middle of the extensive basaltic terrain of the Columbia Plateau. There are other thick basaltic sections in the Northwestern United States in Idaho and Oregon. These basaltic terrains are geologically young, and are tectonically active.

Columbia Plateau basalt is commonly intensively jointed in a columnar (i.e., vertical) fashion but these joints may be filled with alteration products (predominantly clay minerals), and so the rock mass has low permeability. Such masses of low permeability rock are being investigated as potential repository horizons. However, other basaltic strata in the section are fractured and not sealed by alteration products. There are also sedimentary interbeds within the section that are water-bearing. The section at Hanford thus comprises a system of alternating aquifers and zones that are relatively impermeable to water. Groundwater flow through heterogeneous fractured media like these are imperfectly understood. Neither theory nor models exist today for such complex flow.

The partially altered fractured basalt and the sedimentary interbeds between the basalts have moderate to high sorptive capacity. The mineralogy of the altered fracture zones and sediments is different from that of the unaltered basalt, and so, sorptive properties of all the minerals in the fresh and altered basalt as well as the sediments must be determined in order to model radionuclide transport. An intensive program of laboratory studies is underway to develop these data before 1980. The water in the horizons where most flow occurs usually has low ionic strength. Basalt apparently has the ability to tolerate a high thermal load in a repository, but no actual field heater tests will be made until 1979.

7F. Tuffs.

Tuff is an extrusive geologic rock produced by volcanic activity; it has a broad range of physical, chemical, and mechanical properties. Although tuffs have not been identified previously in the United States as a candidate geologic medium for waste repositories, they are currently being evaluated by Sandia and Los Alamos as well as USGS. Japan has identified tuff as a possible repository medium.

Two different forms of tuff are of interest for repository use. The first is "densely welded" tuff, which can have high density, low porosity and water content, and a high level of thermal stability. The compressive strength, thermal conductivity and thermal expansion of densely welded tuffs are comparable to those of basalt. The second is zeolitized tuffs which have low density, high porosity, a high water content and extremely high sorptive properties for radionuclides. Zeolitized tuffs have moderate compressive strength, and a moderate thermal conductivity.

Dehydration of some zeolites begins about 100 degrees C. It has been proposed that this fact coupled with the low thermal conductivity compromise the usefulness of zeolite tuff for a repository. Zeolites heated at temperatures in excess of a few hundred degrees C could release fluids which could lead to hydrofracture of the medium or decomposition to new materials with less sorptive capacity. Due to these effects, use of zeolitized tuffs will impose constraints on thermal loading of a repository.

Whereas zeolitized tuffs are limited by thermally induced changes, densely welded tuffs are less limited by such constraints. An important geologic feature which makes tuffs of great interest is that some large deposits of welded tuff are underlain by zeolitized tuffs. Preliminary data (58) show that some welded tuffs can be held at 500 degrees C without significant change in their mineralogy. Consequently, it appears that it might be possible to place radioactive waste, without restrictive limit on temperature, in the welded tuff with its high thermal stability and maintain the significant benefit from the added protection of a highly sorptive barrier underlying the repository. A two year work plan has been proposed at the Nevada Test Site to assess the viability of tuffs as a geologic medium suitable for a repository and to identify suitable areas.

Welded and zeolitized tuffs are widespread and occur in thick sections in the Western United States though they have not yet been sufficiently characterized as to their homogeneity and their hydrologic characteristics. Most tuffs in the Western United States are relatively young geologically, and yet they have been broken into blocks tens of kilometers in size by tectonic forces that were active during and after the time of their eruption. The hydrogeologic environments in which tuffs occur are dominated by topographic features that reflect the tectonic activity. However, a single hydrological system in the Western U.S. can be large enough to include many such blocks of zeolitized tuffs tens of kilometers in size as in the case of the Nevada Test Site. Potentially acceptable sequences of welded and zeolitized tuffs at NTS are located beneath Yucca Mountain and the Timber Mountain caldera. Specific exploration (27) is underway to confirm this evaluation.

A potential difficulty with welded tuff is that it may have significant fracture permeability. For this reason exploration of tuffs is in part directed toward idenfifying occurrences of welded tuffs situated above the water table (58).

7G. Unsaturated Rocks

Water tables 200-600 meters deep occur beneath certain valleys and mesas of the Southwestern United States. Alluvium, tuff, sandstone, basalt, and many other rock types comprise the strata in the thick unsaturated zones (that is, the volume of rock between the land surface and the water table) beneath these valleys and mesas. These unsaturated zones have been proposed as potential repository sites (59-61).

The major assets of this concept are:

(a) The radioactive wastes will be placed several hundred meters above, rather than hundreds of meters or more below the water table;

(b) Under present climatic conditions transport of radionuclides down to the water table is negligible (due to the near-zero mean annual ground-water recharge);

(c) Alluvium, tuff, and sandstone--rocks commonly found in unsaturated zones--have moderate to high sorptive capacity for radionuclides;

(d) selected thick unsaturated zones occur above regional groundwater basins with flowpaths on the order of 50-100 kilometers; such long ground-water flowpaths provide an major barrier to radionuclide transport to the biosphere;

(e) thick unsaturated zones occur within large Federal tracts of land that have been closed to the public for decades and which contain few boreholes or abandoned shafts; and

(f) relative ease of repository construction and waste retrieval.

Major liabilities of the concept include:

(a) Surface cooling of the wastes for several decades will be required prior to emplacement in certain media. The rocks comprising unsaturated zones have thermal conductivities one-half to 1/30 that of salt; hence the thermal loading for a repository in alluvium, for example, would have to be held to below 100 degrees C. On the other hand, TRU wastes might be emplaced in alluvium with no requirement for cooling;

(b) In the event of a return of a wetter climate to the Southwest (such as existed there prior to 10,000 years ago), groundwater flow vertically through unsaturated zones would undoubtedly increase somewhat, although inundation of the wastes by a rising water table is unlikely;

(c) the relatively shallow (150-300 meter) burial of the wastes might invite penetration by future man; on the other hand, the very deep water tables would discourage such penetration say for irrigation waters.

Considerable research, perhaps taking as long as a decade, is required to quantitatively evaluate this concept. This concept relies on the hydrologic environment, rather than on a rock type, to provide the major barrier to radionuclide transport.

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