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PLAN FOR IDENTIFICATION AND GEOLOGICAL CHARACTERIZATION OF SITES FOR MINED RADIOACTIVE WASTE REPOSITORIES

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Prepared by Subgroup 1 of the Earth Science Technical Plan Working Group, U.S. Department of Energy and U.S. Geological Survey, Department of the Interior

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EXECUTIVE SUMMARY

The initial draft of the Earth Science Technical Plan (ESTP), January 1979, was prepared by a Working Group composed of representatives from the Department of Energy (DOE), some DOE contractors, and the U.S. Geological Survey (USGS). The initial ESTP contained a recitation of earth-science questions, status of answers to the questions, and a listing of current research projects related to the concept of establishing mined repositories for the disposal of radioactive wastes. To assist the Working Group in preparing a second ESTP draft, five subgroups were formed to analyze specific areas of concern in greater detail. Subgroup 1 considered the subjects of Site Identification and Characterization. An interim report of the subgroup was submitted to the Working Group in August 1979.

The present report is the result of Subgroup 1 deliberations during subsequent working sessions held from August 1979 through January 1980. Highlights of this report follow:

- Subgroup 1 recommends that the national effort to identify disposal sites for highly radioactive wastes include a stepwise national screening process.

- The recommended national screening process involves identification and evaluation of successively smaller land units starting with Provinces, which together encompass the 48 conterminous States, that in turn are successively subdivided into Regions, Areas, and Potential Sites. Each subunit is about an order of magnitude smaller than the area within which the subunit is included.

- At each screening stage, the process involves (1) geologic characterization of land units necessary to, (2) delineate and (3) identify (rate) subunits, from which to (4) select subunits for more detailed characterization.

- Rating of subunits is achieved by comparing characteristics of particular subunits with an adopted set of technical criteria that stress isolation through a system of multiple barriers.

- Selection of subunits for further study is made by the U. S. Department of Energy.

- The screening process exclusively uses available data up to and including the Region to Area identification stage.

- Limited field work may be needed at the Area to Potential Site identification stage.

- It is recommended that geologic factors be the sole basis for identifying Regions and Areas for further evaluation. After Potential Sites are identified but prior to the selection of Potential Sites for detailed characterization, it is recommended that other (non-geologic) factors such as land use, accessibility, economics, environmental impacts, etc. be evaluated in parallel with the geologic factors.

- It is recommended that a "Province Working Group" be formed of scientists from Federal and State agencies, universities, and the private sector to implement the screening process. This group would advise on data needs, analyze the data compiled during characterization, compare the interpreted conditions with an adopted set of technical criteria, and rate all land units at each screening stage as favorable, unfavorable, or deferred.

- The cost to identify 26 hypothetical Potential Sites is about 200 million dollars and requires about 1,000 man years of effort.

- The first Potential Sites could be identified 3 years after initiation of the screening process in a Province.

- o Scientific manpower may not be available to characterize and screen all Provinces concurrently.

- o The current Nuclear Waste Terminal Storage exploration program is a mixture of two principal historical approaches to site identification; (1) looking for favorable locations that contain a given candidate host rock, and (2) looking for favorable locations and host rocks on dedicated nuclear reservations. The screening process as herein recommended looks for favorable geohydrologic systems within the conterminous United States without considering initially the type of land use or preselecting a host rock but will utilize the data and analyses from past and ongoing studies. The recommended approach is designed to be comprehensive and provide greater assurance that suitable environments containing multiple barriers will not be overlooked.

- o Following the selection of a Potential Site, characterization requires extensive field work and laboratory testing to acquire quantitative information upon which to base site qualification decisions.

- o Characterization of each site through the granting of a license to construct is estimated to be on the order of 60 million dollars and require 180 to 340 man years of effort. Costs of characterization during construction and operation are estimated to be less than 5 million dollars. Construction costs have not been estimated.

- o Techniques are available for acquiring sufficiently detailed site characterization data. However, improved techniques are desirable for measuring hydraulic conductivity in rocks of low permeability, for dating ground water, and for characterizing fracture flow systems including the effects of thermal perturbations caused by waste emplacement. It is recommended that more basic data be obtained on sorption characteristics of rocks under field conditions and characteristics of candidate host rocks. Improved techniques for analyzing large masses of earth science data will be useful in the screening process for Regions and Areas.

- Monitoring the geologic effects of a repository can be done during construction, operation, and post-closure phases of the facility development. Measurements to determine changes in land-surface elevations and near-surface rock temperatures can be continued into the indefinite future. Measurements of changes in the hydraulic gradient and water quality of the ground-water system, particularly downgradient of the site, could be continued indefinitely during the post-closure period. The exact nature of post-closure monitoring, if any, is better identified at the end of the operational period of the repository.

INTRODUCTION

The concept of the Earth Science Technical Plan (ESTP) for mined geologic disposal of radioactive waste was first discussed formally on August 25, 1978, in a meeting at the Department of Energy (DOE) Germantown, Maryland, among representatives from DOE; the Office of Nuclear Waste Isolation (ONWI), Battelle Memorial Institute; and the U.S. Geological Survey (USGS). ESTP objectives are to formally organize the earth-science research tasks directed toward licensing a geologic repository for radioactive waste, to show how these tasks address the principal remaining technical questions related to geologic disposal of nuclear waste, to identify technical questions that require additional attention, and to identify priorities for future work. A Working Group prepared a draft report (Office of Nuclear Waste Management, DOE and U.S. Geological Survey, January 1979) as a first step in the preparation of the ESTP. Subsequently, the Working Group decided that formation of a meaningful and comprehensive plan would require more detailed consideration of several topics identified in the Work Breakdown Structure (WBS) of the ESTP. To this end, subgroups were organized in the following areas:

Subgroup 1. Site Identification and Characterization (ESTP WBS items 1.0 and 2.0)

2. Waste-Media Interactions (ESTP WBS item 3.1)
3. Rock Mechanics (ESTP WBS item 3.2)
4. Sealing of Shafts and Boreholes (ESTP WBS item 3.3)
5. Earth Science Aspects of Long-Term Public Risk Analysis (ESTP WBS item 4.0)

The ESTP Working Group prepared a draft charter for each subgroup. The Subgroup 1 charter, as initially modified by the Subgroup in June 1979, is given below:

> In general, the process of site selection should aim at the identification and characterization of a set of geologic and hydrologic conditions and processes that will combine to effectively isolate radioactive wastes from the biosphere for the period of time necessary to ensure an acceptable degree of protection for public health and safety.
>
> Subgroup 1 will develop a plan that will provide information necessary to identify and characterize sites. This plan will outline the phases of work necessary to select geohydrologic regions potentially suitable for locating repository sites and, in turn, the exploratory work needed to select potential sites. The plan will describe the work needed to characterize a candidate site after it has been selected. The site characterization plan will provide for the acquisition of data required for licensing requirements. Estimated time required to accomplish each increment of the plan will be included.
>
> The plan will discuss the observations necessary to establish baseline conditions of hydrologic and geologic parameters for use by those concerned with monitoring of the construction, operation, and post-closure effects of the repository.
>
> The plan for site identification and characterization will define the data required, including those required for licensing, and the methods by which these data can be acquired. Attention will be given to approaches which minimize the use of techniques which might adversely disturb a potential repository site. If, in the opinion of Subgroup 1 existing technology is inadequate, and development of new techniques could provide significant improvement in our ability to characterize a site, research and development needs will be identified. Emphasis will be placed, however, on the areas identified in Sections 1.0 - 2.0 of the Work Breakdown Structure (WBS) on pages 13, 14, and 15 of TID-29018 [Draft, "Earth Science Technical Plan for Mined Geologic Disposal of Radioactive Waste" (January 1979)].
>
> Subgroup 1 will expand upon and address the technical questions listed in Sections 1.0 and 2.0 on pages 23 and 24 of TID-29018 (Draft).

Pursuant to this charter, the present report describes a plan for screening land units in stages, based on geologic* considerations, with the ultimate goal of identifying several potential sites from which will be selected one or more sites for developing repositories. It also estimates cost and time required. The screening process involves four principal steps: (a) geologic characterization of a land unit; (b) delineation of subunits; (c) identification (rating) of subunits that appear to be suitable for more detailed study on the basis of geological analyses; and (d) selection of subunits for more detailed geological characterization at the next screening stage. The process begins with subdividing the conterminous part of the Nation into broad Provinces of grossly similar geologic characteristics. The Provinces, in turn, are subdivided into Regions, Areas and Potential Sites. Each successive stage of the screening process requires the collection and compilation of sufficient data to allow a comparison of geologic characteristics of the environment against a set of technical criteria.

In view of the objective of providing effective nuclear waste isolation, the potential for subsurface transport of radionuclides to the human environment is the essential element to be considered in developing criteria. General consideration (factors) are provided for the development of geologic criteria that would be used in the initial steps of the screening process. Whereas each of the factors may not be pertinent to a given area, the criteria developed should include all factors to assure that currently recognized or anticipated technical concerns are addressed.

The process suggested for the identification and characterization of the geologic environments involves the active participation of working groups of scientists with special expertise, whose members may be drawn from State and Federal agencies, universities, and the private sector.

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*"Geologic" as used in this report, includes geology, hydrology, and related earth sciences, although in places the specific terms or combinations of these terms are used.

From the Province-through-Area levels of screening, available published information will be the principal source of data. Few or no field surveys or exploration will be performed through the initial stage of characterization of Areas. At the stage when apparently favorable Areas have been identified and recommended to the DOE, it will be necessary to further characterize selected Areas for the purpose of identifying Potential Sites. Such characterization may involve a certain amount of test drilling, geophysical exploration, and possibly in-situ testing.

The plan for screening geohydrologic environments leading to the identification and characterization of Potential Sites considers only geologic factors. Before the stage of selecting Potential Sites, however, non-geological factors need to be considered. Analyses of these non-geologic factors will be done by others, concurrent with the geologic characterization of Areas and identification of Potential Sites (Fig. 1). These factors would be related to the requirements of the National Environmental Policy Act of 1969 as amended, the Federal Land Policy and Management Act of 1976, and related environmental legislation concerned with ecology, meteorology, land use, demography, and a variety of scenic, historical, archeological, institutional, economic, and societal concerns.

DOE is currently organizing an effort to develop a comprehensive National Radioactive Waste Management Plan which would consider all factors, geologic and non-geologic, technical and non-technical. The ESTP will be a part of that comprehensive plan.

When the Potential Site is sufficiently characterized and seems suitable for an NRC license application to construct a repository, the site is then classified as a Candidate Site. After regulatory approval for construction, the site is classified as a Qualified Site. Following construction and the granting of a license to operate, the site becomes a Confirmed Site (Fig. 1).

The detailed geologic characterization of Potential and Candidate Sites will require extensive, detailed field investigations, laboratory measurements, and theoretical studies. Although present techniques for site characterization are generally adequate, some research and development is needed in a few areas to improve measurement and analysis techniques. The data to be obtained in the process of site characterization will also provide the type of baseline information required by those concerned with monitoring the construction, operation, and post-closure effects of the repository. The latter would include measurements to corroborate predictions produced by modeling near-repository ground temperatures, land-surface movements, gaseous emanations, and background radioactivity.

IDENTIFICATION OF POTENTIAL SITES

Waste isolation is a national problem. Subgroup 1 judges that the process of identifying environments potentially suitable for waste isolation should consider the entire conterminous United States.

Subgroup 1 developed and recommends an approach that initially considers the conterminous United States and which uses a screening procedure for identifying potentially suitable repository sites.

Other approaches to identifying suitable disposal sites have been and are being currently implemented; still others may be feasible. This document proposes that geologic factors should be the paramount consideration for identifying favorable land units from which to select disposal sites, because the geologic environment provides the isolation of radioactive wastes from the environment. Non-geologic factors such as ecologic impacts, current land-use, or cumulative risks relative to waste transportation could be utilized to initially screen the country for acceptable disposal areas; however, the public perception of the importance of these factors changes in relatively short time frames; therefore, their utility for identifying sites with long term isolation potential is secondary to geologic considerations.

Current projects of the Office of Nuclear Waste Management (ONWM/DOE) involve both geologic and non-geologic approaches to identifying potential disposal areas. The geologic projects, managed by the Office of Nuclear Waste Isolation (ONWI), Battelle Memorial Institute, Columbus, Ohio, have identified areas of the country that contain specific host rock types generally considered to be favorable for emplacing nuclear heat-generating wastes. Subsequent to initial screening, based on host rock occurrences, ONWI has and will continue to evaluate a comprehensive set of geologic and non-geologic factors in order to identify specific candidate disposal sites. DOE is additionally conducting evaluations of the waste disposal suitability on two of its nuclear reservations at Hanford, Washington and the Nevada Test Site. These projects employ a screening approach to lands administered by DOE at Richland, Washington, and Las Vegas, Nevada, respectively. Each of the current approaches could be expanded to include the consideration of a greater number of rock types or additional Federal lands. For more information on the technical approaches of ongoing site-identification activities, the reader should refer to the project plans of individual projects (See references identified in part by RHO-CD-132 REY3, May 1979; NVO-196-9, March 1979; ONWI-19, February 1979; and SAND-79-1771, September 1979), and Appendix D of the ESTP Working Group second draft of 1980.

The sequence of events developed by Subgroup 1 for national screening and geologic characterization of nuclear waste disposal sites is presented in Figure 1. The chief functions of the ESTP are (1) to identify specific geologic data needs which emerge in the process of implementing the mined repository concept and (2) to determine how the data could be gathered, analyzed, and evaluated for the timely identification of potential repository sites. The recommended approach is designed to expand areal considerations to those portions of the country not currently being evaluated by DOE, to provide greater assurance that suitable environments containing multiple barriers will not be overlooked, and to provide a means for involving the States in the national site screening process.

Approach

The procedure for the identification of Potential Sites is visualized as being considerably different from that required to characterize a site in detail. The former procedure relies to a great extent on currently available data and considerable judgment. The later requires detailed confirmatory quantitive data and, therefore, is fieldwork intensive.

Not all parts of the country will contain suitable features for locating repositories. It is likely, however, that on the basis of geologic considerations several environments, including at least one from each Province may be expected to be suitable. Of those that seem promising, some will present a more desirable set of conditions than others.

Screening Process. The screening process, as diagramed in figure 1, is designed to result in consideration of successively smaller land units (Table 1, page 14). Note that any particular unit can depart appreciably from the average size indicated.

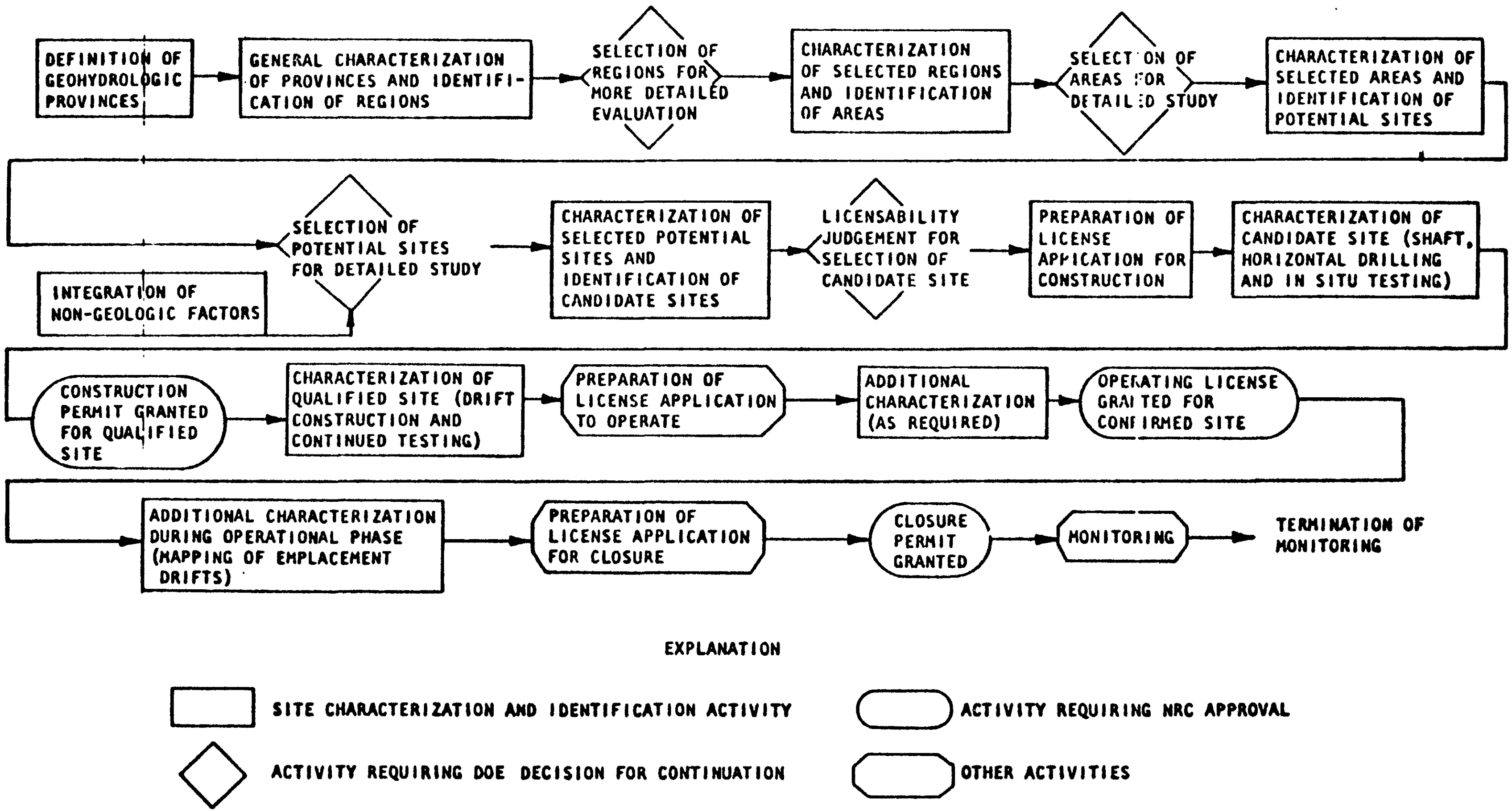


Figure 1.--National plan for screening and development of nuclear waste disposal sites.

The screening process involves four principal steps at each screening stage: (a) characterization of a land unit; (b) delineation of subunits; (c) identification (rating) of subunits; and (d) selection of subunits for more intensive characterization at the next stage.

Characterization of Land Units - In this step the appropriate level of geologic-hydrologic data from various sources is assembled, analyzed, and formulated into a suitable geologic report about a land unit.

Delineation of Subunits - The unit is divided into a comprehensive set of subunits. The subunits, which are delineated on a map, encompass the entire area of the larger unit.

Identification (Rating) of subunits - All subunits are compared with criteria to identify either favorable, unfavorable, or deferred subunits. Deferred subunits at this step will usually be those for which insufficient data are available to make a judgment but may be considered at a later date if sufficient data become available. In the event that no favorable subunits are identified, previously deferred subunits would need to be reconsidered.

Selection of subunits - From among the group of subunits which appear to be favorable, only a few may be selected by DOE for further detailed characterization. Those not selected from this group would be subsumed under the deferred status, perhaps in a subgroup termed favorable-deferred to distinguish from those subunits deferred because of lack of data. If the number of favorable subunits at the Region and Area stages is large and their characterization would overwhelm the available fiscal and/or manpower resources, DOE in its selection process may apply other criteria (eg socio-economic and environmental) to select a tractable number of subunits for additional study.

The two principal reports required at each screening stage are: (1) a description (characterization) of the land units under consideration and (2) a documentation (identification) of the basis for classifying the subunits as favorable, unfavorable, or deferred.

The evaluation of Regions and Areas within a Province would require about two years total. Although the technical effort required for Regional analyses is less intensive than that for Areas, the experience gained in the Regional analysis will provide valuable experience and establish procedure that should allow for more effective Area screening.

Table 1.--Classification of land units for screening procedure

Unit	Approximate Area, Square Miles	Basis of Identification
Nation	3.7×10^6	Geographic - conterminous 48 states.
Province	10^4 to 10^6	Physiographic or broad stratigraphic system.
Region	10^3 to 10^5	Dominance of a structural style or two; fairly well defined geologic-hydrologic system but perhaps with many exceptions.
Area	10^2 to 10^3	Well defined geologic-hydrologic system; few exceptions. Suitable for detailed quantitative appraisal.
Potential Site	10^1	Well defined favorable system.

A sequential outline of the screening process is as follows:

Nation to Province - Provinces will be identified primarily from a geohydrologic viewpoint and will provide a manageable starting point from which to institute the screening process. The Provinces, some 10 to 15 in number (Fig. 2) will comprise the entire area of the conterminous 48 states, although remaining segments of the Nation may eventually be considered. No classification or screening of Provinces is needed.

Province to Region - Provinces will be subdivided into Regions of some 1,000 to 100,000 square miles based on gross similarity of the geologic and hydrologic setting over fairly large areas. From analysis of the regional setting and application of technical screening criteria, Regions within a Province will be identified for their apparent geohydrologic suitability. Also, at this stage, Regions would be classified as unfavorable or be deferred for potential consideration at some later time. Each Region will be large enough to make non-geologic screening criteria inapplicable to the Region as a whole. Therefore, it is recommended that geologic factors be the sole basis for selecting Regions for further evaluation.

Region to Area - The term Area is applied to a land unit of about 100 to 1,000 square miles. The general procedure used to screen Regions within Provinces will also be used to identify favorable Areas within Regions. From an analysis of the geologic-hydrologic setting and application of technical screening criteria, Areas will be identified as to their apparent suitability. Consideration of some non-geologic factors may seem appropriate at this stage; however, this subgroup believes that many of these factors are too subjective and ephemeral to be applied effectively at this early stage of the screening process.

Area to Potential Site - A Potential Site is envisioned as a land unit of about 10 square miles. Obviously not all places within a favorable Area will be satisfactory for a repository site. For instance, localities near discharge points are unfavorable; Potential Sites will be sufficiently up the ground-water gradient to provide a ground-water residence-time buffer. It is at this stage, too, that some amount of field work will be required to aid in the identification of Potential Sites. Non-geologic factors must be considered before Potential Sites are selected for detailed characterization.

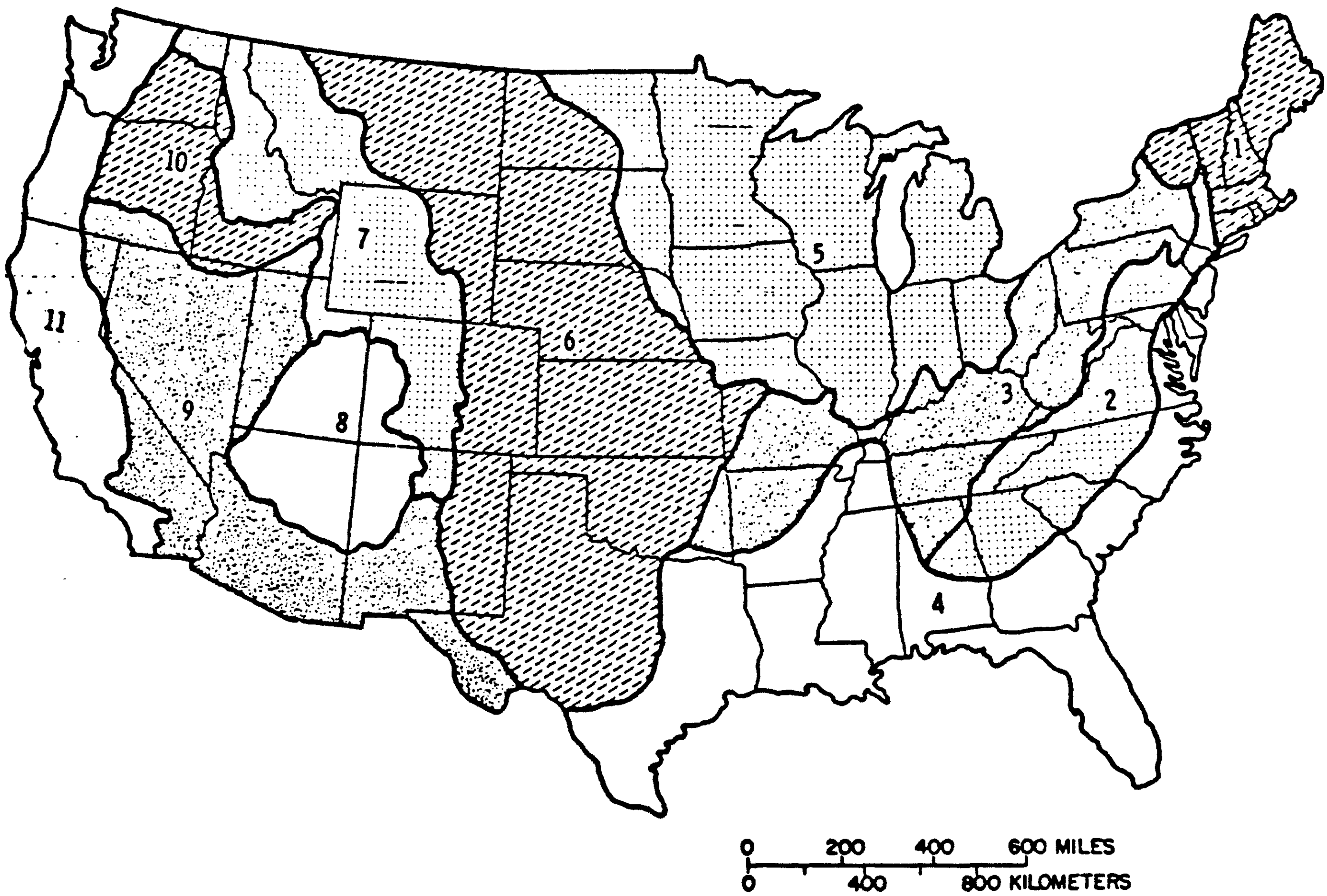


Figure 2.--Provinces suggested by ESTP Subgroup 1 (Modified from Fenneman, 1928).

See Table 2 for explanation.

Table 2.--Explanation for Figure 2

Suggested Province	States
1. New England-Adirondack Mountains	Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont
2. Appalachian Highlands-Piedmont	Alabama, Georgia, Maryland, New Jersey, New York, North Carolina, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia
3. Appalachian and Interior Plateaus	Alabama, Arkansas, Georgia, Illinois, Indiana, Kentucky, Maryland, Missouri, New York, Ohio, Oklahoma, Pennsylvania, Tennessee, Virginia, West Virginia
4. Coastal Plain	Alabama, Arkansas, Delaware, Florida, Georgia, Kentucky, Louisiana, Maryland, Mississippi, Missouri, New Jersey, New York, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia
5. Glaciated Central Platform	Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Wisconsin
6. Western Central Platform	Colorado, Kansas, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, Wyoming
7. Rocky Mountain System	Colorado, Idaho, Montana, New Mexico, Utah, Washington, Wyoming
8. Colorado Plateaus	Arizona, Colorado, New Mexico, Utah
9. Basin and Range	Arizona, California, Idaho, Nevada, New Mexico, Oregon, Texas, Utah
10. Columbia Plateaus	Idaho, Nevada, Oregon, Washington
11. Pacific Mountain System	California, Nevada, Oregon, Washington

All Provinces are assumed to contain environments which appear suitable for mined repositories. It is recommended that the screening process carry through to the stage that leads to the identification of one or more Potential Sites in all Provinces.

Province Working Group. To carry out the entire screening process, a "Province Working Group" will be established, one group for each Province. This group will consist of scientists whose members may be drawn from State and Federal agencies, universities, and the private sector.

The group will include persons either skilled in the earth sciences and knowledgeable about the geologic conditions in a particular part of a Province or expert in special professional disciplines pertinent to the evaluation of site-related waste management issues. Other scientists could be called on for temporary services, but would not necessarily be permanent members.

The Working Group will function throughout the screening process which is anticipated to span 3 to 4 years for a single Province. Although full-time effort will not be required, only those members who can provide the necessary time should be selected.

The Working Group shall (1) provide special expertise and data, (2) analyze all available data, (3) identify (rate) subunits (favorable, unfavorable, or deferred) using appropriate criteria, (4) identify gaps in the data base that are particularly related to safety considerations, and (5) prepare appropriate reports.

The Working Group will receive considerable background material. Working group members shall identify other data sources and contribute their own published and unpublished knowledge.

Working Groups made up of selected participants will in general devote only a part of the elapsed time to intensive effort. There will be a need for six to eight full-time professionals working with each Province Working Group. Others may be expected to devote perhaps one-quarter to one-half of their working time to the Working Group during active periods. There is a probable need for consultants to assemble certain types of data.

Rationale for Subgroup 1 Approach. The underlying goal of radioactive waste isolation is to prevent the migration of radionuclides to the biosphere in concentrations that may be unacceptably hazardous to humans. Subgroup 1 believes the screening process discussed in this report will provide for sites that will meet this objective. In addition, the approach satisfies the intent of the National Environmental Policy Act (NEPA) and the recommendations of the Interagency Review Group (IRG) report that address the following: (1) attractive sites be considered wherever they may exist, (2) there be a national distribution of Potential Sites, and (3) State and local representatives be involved in the screening process.

In particular:

1.) The process is objective. Geological factors form the primary bases for screening. More subjective (non-geologic) factors such as economic and environmental impacts are applied only after a favorable geologic environment is identified. The process is ever cognizant of multiple natural barriers in that suitable geohydrologic systems are the focus throughout.

2.) The designation of Provinces within which screening is independently conducted allows (a) criteria to be equitably applied across broad regions (Provinces) without risking the elimination of entire segments of the country by application of a single set of national screening criteria; and (b) Potential Sites to be identified throughout the nation from which regional repositories can eventually be selected.

3.) The screening process is comprehensive in that it systematically considers the entire conterminous United States.

4.) The approach provides for direct state involvement at the outset in data analyses and recommendations that will continue through the identification of Potential Sites.

5.) The process is resource efficient. It provides for a number of Potential Sites from which to choose a few for the more expensive characterization activity. By screening nationwide according to Provinces and geohydrologic settings, the risk is minimized of encountering unacceptable site properties during expensive site characterization.

This screening process will provide high assurance that acceptable sites will be identified. This or any other process for identifying sites will not necessarily identify "best" sites.

Development of Criteria

The Regions and Areas into which the Provinces are to be subdivided should be rated according to the best judgment of the Province Working Group for their potential as providing suitable repository sites within their borders. Screening should be started by the Province Working Group by applying a set of technical criteria to available geologic knowledge. The final rating will remain a matter of judgment, however, representing a consensus of the Working Group members. Development of a set of criteria, factors which are geologically related issues to be addressed by the criteria, should be considered first. Practically all the factors listed below are concerned, either directly or indirectly, with minimizing the risk of moving waste radionuclides by ground water to the human environment.

Repository host rock. The area should be underlain at least in part by a system of rocks containing one or more suitable host rock units. The following factors should be considered:

Mineability - It should be possible to mine the facility using available mining methods and technology.

Thermal conductivity - The thermal conductivity of the rock unit should be high enough to accommodate the thermal stress imposed by the particular waste form without causing serious increase in hydraulic conductivity or detrimental alteration of the waste form.

Fractures - the rock unit should have a minimum of natural and induced hydraulically conductive fractures.

Hydraulic conductivity - The rock unit should have a low hydraulic conductivity.

Dimensions and geometry - The rock unit should be sufficiently thick and extensive in area to accommodate the facility.

Depth - The repository host rock should occur at sufficient depth to minimize the possibility of exposure through geomorphic and (or) tectonic processes.

Homogeneity - The rock unit should be sufficiently homogeneous to make it possible to predict its essential long-term physical properties in advance of mining and development.

Sorption capacity - The rock unit should have a high radionuclide sorption capacity to enhance radionuclide residence time in the flow system.

Geochemical properties - The geochemical properties of the rock unit and contained water should not result in chemical reactions with the wastes which would facilitate the transport of radionuclides from repository sites.

Ground-water flow system. The essential attribute of the flow system is that it provide long residence time before the water enters the biosphere.

Travel time - The rocks in the system between the repository site and the discharge area should have a low hydraulic conductivity, a long flow path, and small hydraulic gradients to provide a long residence time.

Flow direction - Ground water in a substantial part of the area should have a strong downward or lateral component of flow. There should be no upward flow, particularly if the area contains numerous oil, gas, or other exploratory holes or a high potential for such holes being drilled in the future.

Uniformity - The hydraulic characteristics of the system should be sufficiently uniform to permit the spatial extrapolation of these characteristics to the nearest discharge area. In general, it is preferable that rocks along the flow path should have granular rather than fracture porosity.

Sorption - Rocks with high sorptive capacity should dominate along the ground-water flow paths.

Water quality - To minimize the possibility of future intrusion of the repository by water-well drilling, the potential host rock unit should be underlain by and, at least immediately, be overlain by nonpotable water. A potable aquifer system near the surface would minimize the incentive to drill deeper in search of water.

Tectonic conditions. Certain geologic processes resulting from tectonic activity could disrupt the repository environment and facilitate the mobilization of waste radionuclides in ground water, or possibly even directly expose the wastes. The criteria should consider the following areal factors in terms of their effects on potential repository environments:

- Known active faults
- High seismic intensity
- Recent volcanic activity
- Persistent uplift.

Mineral resources. The intent is (1) to avoid mineralized zones at depths greater than the potential host rocks to minimize the possibility of radionuclides escaping from the repository through pre-existing boreholes which could not be sealed satisfactorily; and (2) to minimize the potential of penetrating the repository in the future by holes drilled for mineral exploration or development. In this sense, aquifers containing water of potable quality are considered a mineral resource.

General considerations. It will be difficult to develop a universally acceptable set of criteria involving geologic processes, many of which are imperfectly understood. The point cannot be stressed strongly enough that the use of a generally applicable set of criteria will require a great deal of insight and perception. In addition to the set of criteria to be developed for screening Regions, at least one more set will have to be developed to consider specific, unique features of Areas and differing rock types and to judge the relative merits of Potential Sites. For Candidate Sites, however, additional set(s) of criteria will have to be quite detailed and specific about local geologic characteristics; thus, suggestions for their development cannot be made at this time. It is unlikely (and unnecessary) that a site be ideal with respect to all criteria. Rather, it is sufficient to establish that an adequate, safe, and acceptable site has been identified. Among others, the general geological criteria discussed in the 1977 report of the International Atomic Energy Agency (IAEA), in the 1978 report of the National Academy of Sciences (NAS), and in the 1979 report of the office of Nuclear Waste Isolation (ONWI) would be useful for this purpose.

Designation of Provinces

The primary need for designating Provinces is to provide a starting point of manageable size. The number of Provinces is a compromise between having many small and well-defined units on the one hand and a few large, less well-defined units on the other. Ten to fifteen units seem to be about the most that should be designated (Fig. 2).

The basis for defining Provinces should be that of gross geologic and hydrologic similarity. Physiographic provinces reflect such gross similarities and are convenient to use.

Characterization of Provinces

The Provinces of the conterminous 48 states will be subjected to a screening process to identify the next successively smaller geographic subdivision, the Region. The number and size of Regions in a particular Province will depend primarily upon the dimensions and geology of the Province with emphasis on identifying rock types in a Region. Subdivision should be based on appropriate differences in geologic-hydrologic characteristics. If certain Regions are rejected early in the screening process, the reasons for rejection must be specifically stated. At this early stage of characterization, comparable data should be collected for all Regions within a Province.

Data and Level of Detail Required. Data required are (1) general information about the structure, stratigraphy, hydrology, and mineral resources of the Province sufficient to provide detail for preparation of a geologic map (at a scale of about 1:1,000,000), and (2) a report of approximately 50 pages summarizing the basic geologic and hydrologic data.

Early in the process of data analysis it may become apparent that one or two Regions are more favorable for siting a mined repository than others; for example, the existence of a particular stratigraphic unit or hydrologic setting.

Methods of Data Collection. Data are to be obtained from a general survey of existing public and private literature. These data must be organized and analyzed to identify appropriate information for inclusion into the screening process.

Format of Data Presentation. A 1:1,000,000 scale map of each Province should be prepared to show the areal distribution of geologic and hydrologic features of significance in the screening process. Also to be shown on maps are the following:

- Major bodies of igneous and metamorphic rocks;
- Major structural features such as folds, faults, unconformities, and intrusive contacts;
- Regional ground-water basins and surface drainage, inclusive of sixth-order streams (Horton classification), on hydrologic maps;
- Outcrops of any stratigraphic unit of special interest for waste isolation.

Generalized stratigraphic sections showing the major groups and formations within the Provinces.

Characterization of Selected Regions

A number of favorable Regions from each of the Provinces will be selected for further geologic and hydrologic characterization. The objective of characterizing these selected Regions is to evaluate their potential for waste isolation and to subdivide them into smaller land units (Areas) with a size of about 100 to 1,000 square miles.

In this phase of the screening process, emphasis is placed on identifying relatively uniform rock units and hydrologic settings within the selected Regions. Areas with well-defined geohydrologic systems capable of general quantitative appraisal will be selected within a Region for evaluation in the next step.

Data and Level of Detail Required. To identify favorable Areas, more detailed information on stratigraphy, structure, geologic history, hydrology, and mineral exploitation is required. Regional information should build directly on the data collected during the characterization of Provinces, but appear on maps of larger scale.

Structure contour and isopach maps are needed for each major geological system to emphasize the underground dimensions and structure of potential host rocks. Maps of lithologic units and their surroundings are needed at scales appropriate to reveal internal and external stratigraphic, petrologic, and structural relations. A supporting text should discuss the lithology of each formation or group (as available in the literature) including sedimentary facies, metamorphic facies, foliations, and petrology. Exceptions to broad regional patterns should be noted.

Tectonic maps are required showing the location of all major tectonic elements, including, but not limited to: intrusive and extrusive masses; faults and fold axes; earthquake epicenters; the sense, direction, and age of major displacements; and known capable structures. Available geophysical and hydrological test data should be reviewed to clarify subsurface geology and hydrology.

Hydrologic maps showing the fourth-order surface drainage networks and major ground-water basins are required. If available from existing records, hydrographs of any eighth-order streams should be provided. The location of major aquifers should be noted. The text should discuss transmissivity, withdrawal and discharge points, permeability, porosity, and water use within the Region.

Major areas of mining and (or) drilling should be identified and located on a regional map. If data exist on other potentially valuable resources, including water, they should also be noted. Available literature sources on rock mechanics should be cited.

The geologic history of the Region should be discussed. This should include major orogens and tectonic events that affected the Region and the general impacts of pluvial and glacial climates.

Method of Data Collection. The primary source of data is the published literature. Principal sources of published and unpublished information are the U.S. Geological Survey, the U.S. Department of Energy, State geological surveys, State departments of natural resources, technical journals, and commercial well-log information services.

Format of Data Presentation. The length of text describing each Region is envisioned as about 100 pages. Some items to be discussed include: major rock types, general structure, stratigraphy, hydrology, geologic history, mineral extraction history, potential for future mining, drilling, or quarrying, seismic history, evaluations of Areas and data sources. The discussion should include the relation and importance of each geologic factor to rating the potential of Areas for waste isolation. The criteria for delineating and evaluating individual Areas within a Region and the methods by which the criteria were applied should be discussed.

Maps of uniform scale (probably 1:62500 to 1:125000) should be prepared for each Region showing distribution of geologic and hydrologic features discussed above. Geologic and hydrologic information should be shown on the following maps and sections:

- Bedrock geology;
- Isopach for each geological system;
- Structure contour;
- Tectonics;
- Fourth-order surface drainage net;
- Ground-water basins showing recharge and discharge;
- Water use;
- Earthquake epicenter--chronological occurrence with magnitudes greater than 4.0 (Richter);
- Stratigraphic fence diagrams;
- Areas delineated through the suggested screening process.

Characterization of Selected Areas

Potentially favorable Areas, ranging in size from about 100 to 1,000 square miles will be selected for further characterization based on their geologic and hydrologic properties. The objective of the Area characterization is to identify still smaller land units, referred to as Potential Sites, that appear to have geologic and hydrologic characteristics adequate to provide an acceptable level of radioactive waste isolation from the biosphere. In addition, Potential Sites must be of a size suitable for construction of a deep geologic repository. The basis of this identification will be a well defined geologic-hydrologic system suitable for quantitative appraisal in a reasonable amount of time and with a reasonable expenditure of funds.

The product of this phase of the program will be a report delineating Potential Sites based on geologic factors only and describing the decision process for identifying these sites. The reasons for excluding any Area will be stressed.

To select Potential Sites, detailed non-geologic factors will be considered in the screening process. Such considerations will ensure that the provisions of the National Environmental Policy Act of 1969 as amended, the Federal Land Policy and Management Act of 1976, and related environmental legislation are fully responded to. These non-geological considerations will involve a separate parallel characterization conducted independently, considering such factors as ecology, meteorology, land use, demography, and a variety of scenic, historical, archeological, institutional, economic, and societal considerations. Refer to figure 1.

Characterization of Areas will involve reconnaissance field work, but not the detailed field work that will ultimately be required to characterize a Potential-Candidate Site. Since the objective of this phase of the exploration program is to identify Potential Sites, not to characterize them, it is not necessary that a rigorous Quality Assurance program (of the type normally required for site-specific geologic investigations of potential nuclear reactor sites) be maintained. Field work will include a limited drilling program, both to obtain core samples and to conduct hydrologic testing. Aerial photography and remote sensing may be used to identify the presence of any previously unsuspected structures and hydrologic features. New geophysical surveys may be required to support and confirm those already available. Some geologic mapping may be initiated in selected Areas to confirm stratigraphic and structural details and relationships.

Collection and evaluation of field data for characterizing Areas within a Region are estimated to require about two years to complete.

Geologic considerations stressed in the Area-to-Potential Site phase of the screening process will include structure, stratigraphy, hydrology, mineral resources, and geologic history. All geologic information pertinent to screening down to Potential Sites within the Area will be documented and illustrated (data presentation should be at some consistent scale) by the following:

- Bibliography;
- Descriptive text;
- Regional physiographic map;
- Geologic map;
- Isopach maps;
- Gravity and magnetic maps (if available);
- Stratigraphic sections;
- Structure maps;
- Topographic map;
- Map showing areas of mineral and hydrocarbon extraction;
- Maps to illustrate such hazards as subsidence, cavernous or karst terrain, extreme weathering, landslide potential, etc., as required.

Structure. All tectonic features observable at the surface will be delineated and described. These will include intrusive bodies, extrusive masses and vent areas, faults, and fracture and joint trends. Geochronology of structural events will be analyzed. The historical seismicity of the Area will be documented to help identify potentially active structures and indicate general ground motion potential.

Stratigraphy. Available stratigraphic descriptions may be supplemented by test drilling to obtain cores. Drilling data also provide a means to correlate existing well logs within the Area. Surface and aerial geophysical surveys may be conducted to support interpretation of subsurface geology. Core samples will be tested in the laboratory to determine physical and chemical properties of potential host rocks and adjacent media. Isopach maps, and facies distribution maps, of each formation and important members, as well as lithologic and mineralogic descriptions, will be prepared.

Hydrology. Available hydrologic information may be supplemented by drilling hydrologic test holes. A set of hydrologic properties will be obtained at each well drilled. The distribution of hydraulic potentials in the Area's ground-water basin or basins will be determined. The hydraulic conductivity of selected stratigraphic units will be determined by field or laboratory testing. A detailed map of all ground-water withdrawal and natural discharge locations will be prepared and accompanied by a description of water use. Hydrographs of fifth-order and higher streams in the area will be prepared and flood recurrence intervals calculated. Chemical and isotopic dating analyses will be performed on ground-water samples collected from wells and discharge points. Ground-water residence time will be calculated.

Mineral Resources. From historical records, previous mineral and petroleum exploration/production within the Area will be tabulated. For each resource, value and volume of the extracted resource will be calculated. The potential for future production will be evaluated, and locations having identifiable potential will be delineated and described.

Geologic History. A detailed description of the geologic history will be prepared with special emphasis on the events of the Pleistocene and Holocene epochs. A preliminary erosional history will be geomorphically analyzed with emphasis on vertical incision, lateral erosion, and regional denudation rates.

General. The documentation of geologic information used to identify potential sites will be synthesized as a preliminary report on the characteristics of Potential Sites. This report will, in turn, serve notice to all interested parties that the site in question is identified as potentially suitable for construction of a repository, pending further detailed study and evaluation.

SITE CHARACTERIZATION

Site characterization activity begins after a Potential Site is chosen for detailed study. The Region-to-Potential Site screening process should provide a high level of confidence, based primarily on existing information, that a site will be demonstrably suitable for providing adequate containment of radioactivity emanating from emplaced wastes and their chemical derivatives. After Potential Sites are identified, however, those selected will require extensive field work to verify the preliminary judgments made during the screening process and to allow rigorous quantitative appraisal of the site's containment qualities.

A Potential Site includes more than the surface area of the site and the adjacent buffer zone and more than the subsurface volume excavated for waste emplacement. For instance, the ground-water flow system leading from the immediate site area is a geologic factor to be considered in characterization of a Potential Site. Each geologic factor that is potentially affected by, or that potentially affects, repository performance possesses unique characteristics. These factor-dependent characteristics define the geographic area for which detailed characterization is needed to adequately understand the interaction of the repository and its environment.

Therefore, when one speaks of a "site" for characterization purposes, care must be taken to distinguish:

- The geologic factor of concern;
- The volume or area potentially impacted by that factor;
- The level of detail that will provide sufficient understanding of potential effects on repository performance to allow reasonable decisions on site suitability and, if necessary, predictions and consequent assurances regarding risk factors related to public health and safety;and
- The costs, in terms of both time and resources, likely to be incurred in obtaining the desired level of detail.

At no time will "complete" characterization ever be achieved for any site. A definition of "sufficient characterization" is therefore a matter of judgment, and characterization will always be less than could be obtained with additional effort and time. Although the subjective nature of site selection and verification cannot be eliminated, comprehensive site characterization programs can provide very high levels of confidence about a site's containment qualities. The final judgments regarding suitability will be made only after subsurface excavation and related site inspections have been performed. It is the opinion of the subgroup that existing characterization methods can provide the desired levels of confidence. Improved methods are not required, although they would be useful in achieving greater resolution during site characterization.

Prior to construction and, presumably, before a decision is made to apply for a construction license, direct observations of the emplacement zone and surrounding rocks are limited to a few drill holes. The information required to allow a confident decision includes data on the regional stratigraphic, structural, tectonic, and hydrologic settings of the site. Much of these data must be obtained at some distance from the emplacement site. Well accepted geophysical techniques provide a means for obtaining ancillary data at the repository site to refine the correlation of rock properties between drill holes and to extend the regional information to the site. Preconstruction characterization is designed to achieve a highly confident verification of judgments made when the Potential Site was selected for detailed study.

After construction begins, the focus of site characterization shifts to direct observations of the emplacement zone as shafts, horizontal core holes, drifts, and waste emplacement holes are progressively constructed. Subsurface mapping of fractures, lithologic variations, thermal and mechanical properties, and the determination of hydrologic conditions are an essential part of site characterization. Site characterization during construction provides the final preoperational increment of information upon which to verify previous judgments of site suitability.

The geologic subject areas that require characterization for each site include:

- Stratigraphy
- Structure
- Ground-water Hydrology
- Surface-water Hydrology
- Physical and Chemical Properties
- Geologic History
- Mineral and Energy Resources

In this section each of these topics is subdivided for discussion as follows:

- Geologic Factors--a definition of each major geologic subject area of concern including, where appropriate, a listing of geologic factors that can be measured to provide the needed characterization; and a statement about the topic's importance in assessing repository containment potential.
- Characterization Methods--the methods best suited to provide characterization.
- Limits to Characterization--the reasonable current and projected limits of geologic science to definitively characterize the subject areas of concern.
- Format of Data Presentation--a suggested format for presenting characterization data that will allow comparative evaluation of individual or combined factors from alternative sites.
- Estimated Resource Requirements--an estimate of elapsed time, dollars, and manyears required for characterization.

Because characterization of Potential Sites requires a significant amount of field work and data analysis, this chapter presents an expanded discussion of data needs and the level of detail required for each geologic subject area. A summary of the site characterization requirements is presented in Table 3 at the end of this chapter. It is unlikely that all the characterization activities discussed below will be required for each Potential Site. It is not within the scope of this general plan, however, to discuss the particular activities required or desirable at specific sites. Obviously, these will depend on the nature of geological conditions at each particular site. Therefore, judgments must be made regarding the applicability and need for the site characterization activities discussed below.

Stratigraphy

Geologic Factors. Knowledge of stratigraphy is fundamental to understanding the waste isolation potential of an area because it provides a generally accepted nomenclature for describing, mapping, and areally correlating all pertinent physical characteristics of the rocks.

Permeability, sorption, thermal conductivity, and other factors are important for understanding and analyzing the effects of a repository on adjacent rock masses. These factors correlate to some degree with rock type. Before subsurface excavation begins, measurements of such physical properties can be obtained only from a few widely distributed sampling points scattered throughout the region of interest. By applying stratigraphic principles, one may deduce the three-dimensional distribution of these properties and develop a conceptual model of the region of interest. It is not the stratigraphy, per se, that is important for effective management of nuclear wastes, but it is the conceptual model inferred from the stratigraphy that allows both geometrical characterization of physical properties governing the radionuclide transport and subsequent quantitative analysis of repository effects. The level of confidence assigned to quantitative predictions of repository effects on a rock volume is highly dependent on the qualitative confidence obtained about stratigraphic patterns in the area of interest.

Factors that can be measured for stratigraphic characterization are chemical and mineralogical constituents; textural attributes; appearance of individual rock samples or outcrops; geophysical properties (acoustic, electric, magnetic, etc.) of rock masses; and geometric relationships among rocks of differing character.

Characterization Methods. The methods best suited for stratigraphic characterization are field mapping, laboratory study of drill cores and logs, geophysical surveys, conceptual modeling of depositional basin evolution, and digital modeling of three-dimensional stratigraphic patterns.

Field mapping of surface and near-surface lithologic units at a scale of about 1 inch = 200 feet should be performed within and immediately surrounding the emplacement site. An absolute minimum of one, and preferably three, holes should be drilled and cored beyond emplacement depths within the areal confines of the emplacement zone to provide three-dimensional control for subsurface stratigraphic interpretations. Both field and core samples should be analyzed petrographically by thin-section, sieve, X-ray, and other analytical techniques. Characterization of lithologic units should include taxonomic classification, facies patterns, primary and secondary mineralogy, constitutive textural ratios, unconformities, buried soils and interbeds, hydrothermal and other alteration zones, and solution cavities. Additional field-based characterization may be required.

Selected field and core samples should be chemically analyzed and isotopically dated. Borehole logs including caliper, density, gamma, neutron, resistivity, temperature profiles, and other logs as needed, should be obtained at all drill holes in the vicinity of the site. Surface geophysical surveys, including high-resolution seismic reflection and electrical resistivity, should be run on a closely spaced grid throughout the vicinity of the waste emplacement zone.

All information from the above activities should be integrated into a conceptual and three-dimensional digital model of the stratigraphy in the repository area. This model should be integrated with more generalized stratigraphic models of the surrounding area which were developed during the Area phase of characterization. If inconsistencies occur between the generalized areal model and localized detailed model, drilling and geophysical measurements should be performed in critical areas to resolve them.

During the construction phase, rock samples should be obtained by horizontal coring of the design repository volume and analyzed in detail to refine the degree of resolution and to modify, if necessary, the stratigraphic model. Tunnels and shaft walls should also be inspected and mapped during construction. The basic stratigraphic model will serve as a frame of reference for assigning values to model parameters related to ground-water transport, thermal conduction, mechanical strain, and chemical properties.

Limits to Characterization. The limits to stratigraphic characterization depend on many factors and cannot be specified on a generic basis. Among the factors that should be considered are:

- Lateral and vertical extent of outcrop areas;
- Structural attitude and complexity;
- Amount, depth, and distribution of subsurface penetrations;
- Contrast in physical, chemical, and lithologic properties between adjacent units (which helps determine geophysical resolution);

- Amount of previous study on similar stratigraphic sequences;
- Depositional environment (e.g., marine strata are generally more uniform than continental strata); and
- History of the depositional basin.

Attempts to select areas that maximize the first five factors may increase the capability to gather stratigraphic information, although associated undesirable conditions are likely to result. For example, extensive previous study of similar environments and a large number of subsurface penetrations indicate a high potential for conflict between mineral resource development and waste management objectives, because most detailed stratigraphic study is concentrated in regions where mineral or petroleum resources are abundant. Extensive outcrop areas generally indicate rapidly eroding regions. High geophysical contrasts in the stratigraphic section may indicate subsurface complexity not readily apparent at the surface, although such high contrasts may also occur in uniformly layered environments. Lateral continuity is difficult to establish in structurally complex terrain, although high structural dips, eroded folds, and fault scarps may expose abundant portions of a stratigraphic section for study. Thus, a balance must be pursued between desires for maximum stratigraphic characterization, and a simple, uniform environment devoid of mineral resources.

Regardless of the complexity or simplicity of any region, uncertainties in stratigraphic correlation between sampling points are unavoidable. This is especially true for small-scale thermophysical and hydrologic properties. Even in the simplest environments, the level of confidence is limited by the distribution of sampling points. The desire to minimize subsurface penetrations in the vicinity of a potential repository compounds this limitation.

Format of Data Presentation. The format for presenting stratigraphic information depends on site-specific geologic characteristics. However, a combination of maps, cross sections, and text is required in all cases. The general level of detail required to allow reasonable portrayal of stratigraphic conditions is provided in the following list:

- Slice maps at a scale of about 1:2400 for each depth interval of about 50-100 feet to a total depth of about 4,000-5,000 feet
  - sedimentary facies
  - structural attributes
  - mineralogical facies (igneous and metamorphic rocks);
- Isopach maps with about 10 ft-contour intervals for each stratigraphic member;
- Stratigraphic columns, sections, and correlation fence diagrams (orthogonal at minimum);
- Detailed text describing all lithologic units, their mode of formation, geometrical relationships, methods of analysis, and relation to the site's containment qualities.

Estimated Resource Requirements. The estimated resources required to obtain stratigraphic characterization depend primarily on the number of drill holes required at a particular site. Additionally, the nature of lateral and vertical facies changes and overall structural complexity will affect the cost of field mapping and geophysical surveying. In a simple region, assuming three drill holes each cored continuously to 5,000 feet, about $5 million should provide the stratigraphic information required for a preliminary safety assessment. Approximately 60 percent of the total expense is required for drilling, 30 percent for geophysics, and 10 percent for field mapping, petrography, and chemistry. Depending on whether the holes are drilled and evaluated sequentially or concurrently, the time required can range from two to four years. More complex environments require costs ranging from $10-15 million and a period of three to six years for similar confidence levels in stratigraphic understanding.

Structure

Geologic Factors. Knowledge of structure is fundamental to understanding an area by providing a means to predict:

- Subsurface distribution of rock types;
- Subsurface conditions and physical properties that vary from those otherwise expected, based upon measurements of non-deformed (e.g., fractured) rocks; and
- Potential for natural or man-induced changes in the conditions and configuration of a rock body.

Knowledge of the structural regime of a region is additionally required to assess potential in situ effects of structural elements (e.g., fractures) on physical properties such as permeability, thermal conductivity and expansion, and shear strength. Incorporating the effects of structure, both large and small scale, into a stratigraphic model provides a more realistic representation of rock properties that affect and determine potential pathways for the migration of radionuclides.

Characterization Methods. The methods best suited for structural characterization are:

- Field mapping;
- Drill core and log study;
- Geophysical surveys;
- Conceptual modeling of tectonic evolution; and
- Digital modeling of three-dimensional structural conditions.

Field mapping can delineate most major structures of concern and provide a statistical sample of regional trends of small-scale features. Features to be mapped include location, attitude, and magnitude of observable faults and fold axes; frequency and attitude of statistically sampled joints, fractures, and foliations; surface trace of lineaments; and distribution and attitudes of all lithologic units. Low priority should be placed on detailed surface characterization of minor structures.

Analyses of oriented cores will include determination of the attitude, frequency, and conditions of all macroscopically and selected microscopically observable fractures, breccia zones, slickensides, and vein fillings.

Electrical geophysical surveys can provide clues about the overall fracture conditions at depth. However, because interpretation of these surveys does not yield unique solutions for the subsurface conditions, extraneous factors that affect interpretations must be evaluated.

Observed drill-core fracture patterns should be correlated, if possible, with data from borehole logs and surface geophysical surveys. In situ stress should be measured (e.g. by hydraulic fracturing) in the vicinity of but not at a repository site. Extensometer and flat-jack measurements may be useful in drill holes and subsurface excavations within the site boundaries.

Limits to Characterization. The limits to structural characterization depend on many of the same factors as for stratigraphic characterization. Understanding of structure cannot be separated from that of stratigraphy.

Although individual structures are produced by rock body stresses acting over an entire region, small spatial variations in resistance to these stresses cause the localization of myriad individual structural features. One can predict that a rock body will probably be fractured to a certain degree; however, the character, location, and even existence of individual, unobserved structures is highly conjectural. Structures cannot be correlated across broad regions because each feature is discrete and physically separated from adjacent as well as distal structures. Structures can therefore be projected geometrically only for limited distances.

The prediction of structural features likely to be encountered at repository depths depends on the scale of the feature of interest. For example, large folds and faults with relative vertical displacements of tens of feet and horizontal surface traces of thousands of feet can usually be observed in the field and projected to the subsurface with a fairly high degree of confidence, although possible changes in orientation with depth must be considered. On the other hand, smaller surface structures such as joints and fractures can be mapped only where a soil cover does not mask the rock surface and then only at the expense of a great deal of time. Confident projection of small-scale surface structures to the subsurface is not possible.

A common approach that avoids complete mapping of all exposed fractures is to sample selected locations and develop rose diagrams which are presumed to statistically characterize the fracture pattern throughout the region of interest. Nevertheless, the desire to limit the number of exploratory drill holes in the vicinity of a repository almost guarantees that unpredicted small-scale structural "anomalies" will be encountered during excavation of the repository. It is doubtful that data from the limited number of drill holes will be sufficient to provide even a reliable statistical representation of subsurface small-scale structures.

Format of Data Presentation. The suggested format for presenting structural information includes:

- Maps at a scale of about 1:2400 (consistent with stratigraphic and hydrologic map scales) of
  - tectonic features
  - rock outcrop patterns
  - structural attitudes of exposed rock units;
- Structural fence diagrams;
- Rose diagrams for surface and drill-core fractures;
- Core indices and fracture histograms for each drill hole; and
- Detailed text describing all known structural features, their condition, mode of formation, distribution, and relation to the site's containment qualities, and the methods by which they were mapped and analyzed.

Estimated Resource Requirements. The resources required to obtain structural characterization of a site are estimated at 2-3 million dollars, assuming that most drilling, logging, and seismic-reflection survey costs have been charged to stratigraphic characterization. About 70 percent of the additional costs are for electrical surveys and in-situ stress measurements, 15 percent for field mapping additional to that required for stratigraphic characterization, and 15 percent for additional drill-core characterization. The time required is the same as for stratigraphic characterization.

Ground-water Hydrology

Geologic Factors. Knowledge of ground-water hydrology is perhaps the most important requirement for understanding the long-term risk posed by construction, operation, and sealing of a waste repository. Transport of radionuclides away from the waste emplacement zone by moving ground water is by far the most likely mechanism by which radionuclide movement from a repository to the biosphere could occur, given at least partial failure of the waste form system. Understanding of the subsurface flow system is fundamental to attempts to predict radionuclide movement directions, rates, locations, and concentrations as functions of time, and, in turn, to evaluate the associated risks to man. Ground-water systems must be found that minimize the consequences of potential transport.

Parameters that can be measured for characterizing ground-water hydrology include porosity, permeability, soil infiltration capacity, percent saturation within the vadose zone, depth to the static water level, pumping yields, location and time of appearance of tracer substance, water chemistry, isotopic ratios, and water temperature.

<u>Characterization Methods</u>. The methods best suited for hydrologic characterization are:

- Field mapping;
- Drill-core study;
- Drill-hole hydraulic testing;
- Ground-water chemical and isotopic analyses; and
- Conceptual and digital modeling of regional flow systems including associated rocks of low hydraulic conductivity.

Field mapping may include locating ground-water discharge areas, especially downgradient, of the repository site. Recharge characteristics might be estimated and mapped based on field study of soils, bedrock, and climate.

Drill-core samples from all appropriate zones should be tested for matrix porosity and permeability. Hydraulic testing of drill holes should include measurement of static head for each hydrologic unit; pump tests and (or) injection tests to measure hydraulic conductivities at appropriate depth intervals including very low conductivity units; and trace-element injection tests to measure both apparent sorption characteristics and effective porosity between closely spaced wells. All test holes and any suitable existing wells in the ground-water basin of the repository site will be monitored for static water level and sampled to determine water chemistry, isotopic ratios, natural radiation, and the temperature of the ground water. Vein- and fracture-filling materials may also be sampled for chemical and isotopic analyses to help define ground-water residence times. The hydrologic data will be integrated to define a three-dimensional model of the regional flow system. This model should be dimensionally compatible with the stratigraphic-structural model of the site. A more generalized, two-dimensional model should be constructed for the region between the vicinity of waste emplacement and all downgradient discharge areas.

Limits to Characterization. The limits to hydrologic characterization are affected by all the uncertainties associated with stratigraphy and structure as discussed in foregoing sections, in addition to the uncertainties inherent in determining the three-dimensional characteristics of the ground-water flow system.

Three-dimensional mapping of any hydraulic head to determine hydraulic gradients is difficult, time-consuming, and expensive, but necessary. A reasonable two-dimensional approximation of a potentiometric surface representing the highest head in a region can be obtained with less difficulty, but such a surface may severely misrepresent head relationships of individual aquifers and between aquifers. Variations of head with depth, especially in multiple, confined aquifer systems, are difficult to characterize and require the measurement of static water levels at various depth intervals in a bore hole. Moreover, such measurements must be made with hydraulic packers inserted to adequately isolate the water of the test intervals from the waters above and below.

Because hydrologic characterization is required for all regions potentially traversed by contaminated ground water, the region for which characterization is required is considerably larger than the site itself. Because of constraints imposed by the amount of drilling that can be done, sampling points must be very widely spaced. As a result, confidence may be low about the accuracy with which the potentiometric surface can be delineated between sampling points.

Most hydrologic systems discharge along diffuse boundaries such as rivers, oceans, and lakes. Recharge, likewise, is diffuse because of its origin in precipitation. These factors combine to make the local and regional definition of ground-water basins difficult. If discharge is into a large water body, such as the ocean, delineation of the precise boundaries of a ground-water basin is impossible.

Even if the regional flow system can be reasonably characterized, its velocity is more difficult to define. Velocity is a function of hydraulic conductivity, gradient, and effective porosity. The characterization of hydraulic conductivity is subject to the same limitations as those for defining subsurface fracture systems. Fracture, rather than intergranular, flow is the most likely transport mechanism in many systems, and therefore, conductivities measured in a laboratory from nonfractured core samples may not even approximate values resident in an in situ rock body. Additionally, because wells may be tested in a region of anomalously high or low fracture density, misrepresentations of the regional conductivity of the depth interval tested may result.

A quasi-independent method for evaluating ground-water flow velocity and subsurface residence times may be provided by isotopic dating of water and fracture-filling carbonate materials (e.g., ^{14}C). However, in view of the potential for natural mixing of old and young water, interpretations of ground-water dating must be carefully evaluated. In summary, a precise definition of ground-water flow characteristics should not be expected.

Format of Data Presentation. The format for presenting hydrologic information includes:

- Maps of the regional water table and potentiometric surfaces for appropriate depth intervals and for each aquifer;
- Flow line maps for each 100-foot interval, for each aquifer within the regional basin, indicating, where possible, flow velocities;
- A map of potential recharge and discharge areas indicating locations and, if possible, quantities;
- Cross sections showing the position of the water table and potentiometric surfaces of individual aquifers, equipotential lines, and vertical velocities of ground-water flow, if known;
- A digital three-dimensional hydrologic transport model of the repository vicinity;
- A two-dimensional transport model of the ground-water basin in which the repository is sited; and
- A detailed text describing all known features of the hydrologic system, their relation to stratigraphic and structural features, their potential effects on waste containment, documentation for the computer programs used in the transport models, and discussion of potential changes in the hydrologic system due to climatic or tectonic change.

Estimated Resource Requirements. The resources required to characterize the hydrology of a site depend largely on the number of hydrologic test and observation holes required at a particular site. In many instances, a central test hole needs to be surrounded by a set of two to four observation holes.

The number of aquifers and intervening zones of low hydraulic conductivity and the size of the ground-water basin in which a site is located also influence the scope of the hydrologic testing program. In a fairly simple geologic environment, assuming five sets of hydrologic test and observation holes, with an average of three holes in each set of wells, about 10-15 million dollars should finance the required characterization in the vicinity of the site. About 80 percent of the costs are for drilling and testing holes in addition to those used primarily for stratigraphic control. The remaining 20 percent is for field mapping and laboratory analysis. These cost estimates assume that three of the five central test holes are drilled for stratigraphic characterization and serve as multiple-purpose holes. The time required can range from 3 years, if the holes are drilled and tested concurrently, to 5 years if in an overlapping sequence. More complex environments could require 15-30 million dollars and 5 to 6 years for hydrologic characterization, assuming a total of 10 sets of test holes comprising a total of 15 to 30 individual holes. These estimates do not include expenses for characterizing the regional hydrology, which may require an additional 5 to 10 drill holes and 2-5 million dollars.

Surface-Water Hydrology

Geologic Factors. Knowledge of the surface-water hydrology is needed principally because of the potential effects of surface water on repository surface construction and operations, and because surface facilities can affect components of the surface hydrologic system. Additionally, a thorough characterization of surface hydrology is required to provide a baseline for use in monitoring repository construction, operation, and post-closure impacts. Parameters that can be measured include distribution of the drainage net, organic and inorganic water chemistry, flow rates, stage, and entrained sediment transport.

Characterization Methods. Methods most appropriate for characterization include:

- Mapping the occurrence of surface-water bodies;
- Measuring flow characteristics and sediment yield at stream gaging stations;

- Collecting water samples for laboratory analysis; and
- Conceptual and digital modeling of the surficial flow system.

Data need to be collected only for the area that is reasonably assumed to be affected by or to affect the surface portion of a repository. As a general rule, it will be adequate to collect data for distances up to 50 miles from the site. The physical, chemical, biological, and hydrological characteristics will be measured and analyzed, and typical seasonal variations and historical extremes for these parameters will be calculated.

Surface-water bodies will be delineated on maps at a scale of about 1:2400. Data on streamflow should be collected at gaging stations on fifth (and higher) order streams; the parameters include flow rate, stage, water temperature, suspended sediment load, and bed load. Water quality data to be collected include physical, chemical, biological, and radiological characteristics. Mean and extreme values for all parameters will be tabulated.

Limits to Characterization. The potential for characterization of surface-water hydrology has few limitations, the most significant being the time needed to develop an adequate statistical base for the wide temporal variations in the hydrologic properties. Otherwise, it is possible to characterize the surface waters to whatever degree is deemed desirable and (or) cost-effective by utilizing an appropiately large data-sampling network, and by increasing the frequency and duration of data acquisition. Short-term periods of record commonly are not useful for characterizing magnitude and variation of the stream flow. Estimates of suspended and bed loads are calculated from stream-flow measurements based on empirical relationships.

Format of Data Presentation. The format for presenting surface hydrological information will include maps showing the location of all surface-water bodies, flood control structures, gaging stations, and sampling points. Data on streamflow, floods, water quality, hydraulic characteristics, chemical characteristics, biological quality, and radiological quality will be presented in tabular form. The locations of all significant water-use intakes will be identified on a map, and tabular data will be presented for municipal, agricultural, recreational, and industrial water use, if any. A supporting text will describe all these features. Additionally, a synopsis should be provided on the flood history of significant streams (fourth order and above) in the drainage basin.

Estimated Resource Requirements. At least 2 years of continuous data collection will be required. Fiscal resources required to collect, compile, and evaluate the required data, as well as to prepare appropriate reports, are estimated to be $500,000, assuming that gaging stations are available. Of this amount, approximately 60 percent will be expended for gaging and sampling, 30 percent for laboratory analyses, and 10 percent for report preparation.

Physical and Chemical Properties

Geologic Factors. "Physical properties" as used here refers to those properties that determine a rock's response to thermal and mechanical stresses and gradients thereof. They include thermal conductivity, thermal diffusivity, thermal expansion, Young's Modulus, Poisson's Ratio, critical strength, bulk modulus, and background radioactivity. Knowledge of these properties is important to understand and predict changes in a rock body that will be induced by excavating a repository, emplacing heat-generating waste, backfilling, and sealing the excavation.

Chemical, or more specifically, geochemical properties refer primarily to the propensity of rock material and associated ground water to enhance, impede, or prevent the movement of radionuclides through a rock body relative to the movement of ground water. The specific properties include sorption and solubility, which vary as functions of temperature, pressure, and solution equilibria. Knowledge of geochemical properties is important to understand and predict movement of radionuclides through the subsurface environment.

Coupled thermal, mechanical, and chemical responses of near and intermediate field rocks may cause changes, either adverse or beneficial, in the ability of the rock mass to contain emplaced radionuclides. In particular, thermal expansion will cause localized compressive and tensional stresses that may result in the creation, opening, or closing of fractures. These stresses, in turn, may change the rate of flow or directions by which water and dissolved radionuclides are transmitted. Thermal and hydraulic properties of the rock will determine the temperature to which emplaced wastes and surrounding rocks are subjected. This temperature, in turn, will affect the rate of chemical reactions that might cause or prohibit release of radioactive isotopes to the ground-water system or create gaseous phases. Subsequent chemical reactions that retard or enhance movement of the radioisotopes in the ground-water system are also affected by temperature gradients surrounding a repository. Adsorption, absorption, ion exchange, and precipitation are mechanisms with great potential for retarding or eliminating movement of radionuclides through rock bodies. Other chemical reactions such as solution, chelation, desorption, and diffusion can cause or enhance radionuclide movement. Chemical and physical properties per se are not of importance to waste managment, but their coupled effects on the containment potential of subsurface environments are of critical concern.

Characterization Methods. The methods best suited for characterizing physical and chemical properties of rocks within the vicinity of a repository site are:

- Laboratory measurements on a wide variety of individual samples;
- In situ measurements in a subsurface test facility carefully located and designed to be as representative as possible of repository conditions;
- Correlation of thermal, mechanical, and chemical properties of rocks with lithologic characteristics such as porosity, density, water content, mineralogy, and structure; and
- Conceptual and digital modeling of the effects of the various properties on each other, on the rock body surrounding the emplaced waste, and on the potential for migration of waste in the ground-water system.

Laboratory measurements will include determination of the coefficients of thermal conductivity and thermal expansion, Young's Modulus, Poisson's Ratio, bulk modulus, critical strength, background radiation, sorption potential (batch and transient methods), solubility, mineralogical transitions, dehydration, density, porosity, and permeability as functions of temperature, pressure, water chemistry, and water movement through gradients simulating repository conditions.

Measurements will be made on core samples from approximately 10-foot intervals from all drill holes in the vicinity of the site and on larger blocks extracted preferably from mines, or at a minimum, from outcrops of rock types similar or identical to those in the vicinity of the site. Detailed microscopic study of molecular and mineralogical affinities for sorbed radionuclides; microstructural response to heat and pressure; and mechanical and chemical effects along fractures will be determined by thin-section, X-ray, mass spectroscopy, electron probe, micro-radiographic, and other appropriate techniques.

In situ tests include heater tests that simulate the expected heat output for the geometry of emplaced waste. Associated measurements will be made of rock temperature, strain, release of hydrated water, gaseous emanations, water chemistry and movement, induced rock structures, mineralogy, and rock stresses as functions of time and distance from the heat-producing source. More sophisticated tests might be performed that include measuring of hydraulic potential throughout the heated zones and tagging ground water with radionuclides to determine in situ retardation mechanisms for radionuclide migration. Post-test analysis of rock samples from the affected region will be performed by methods outlined in the previous paragraph for laboratory testing.

All data on physical and chemical properties will be correlated with stratigraphic and structural variations to determine those lithologic parameters that best allow their incorporation into a three-dimensional digital matrix representing the rock mass at the repository site. These data will then be integrated with the hydrologic data to provide a single digital model which will serve as the basis for calculating the near- and far-term effects of repository operations.

<u>Limits to Characterization</u>. The limits to characterization for physical and chemical properties of rocks must be considered in terms of scale and the degree of heterogeneity. Techniques exist to allow very precise characterization of the properties of interest for small homogeneous samples studied in the laboratory. However, the relation between the properties of small samples and those of an in situ, fractured, heterogeneous rock body is highly problematical.

For several reasons, the apparent conductivity of a rock mass may be less than that measured for a particular rock type. For example, in a fractured rock mass, the thermal conductivity across open, air-filled, or water-filled fractures may be significantly less than the conductivity determined in the laboratory for the rock surrounding the fracture. Movement of water through fractures may remove heat by mass transport, producing an apparent increase in thermal conductivity in the vicinity of the fracture. Additionally, calculated thermal expansion based on laboratory measurements may predicate stresses that exceed the shear strength of a rock. However, fractures provide pre-existing shear planes that can absorb and (or) transmit critical stresses, eliminating the mechanical need for creating new fractures.

Secondary minerals along fractures may have different sorption potentials than fresh surfaces of a rock mass, and radionuclide retardation along a fracture flow path may be significantly different from that predicted from laboratory sorption measurements on samples of crushed or artificially fractured rock. Both the cross-sectional flow area and related effective surface area in fracture-flow systems are likely to be orders of magnitude less than in intergranular flow systems, and sorption predictions based on transient flow measurements in granular materials may erroneously overestimate sorption capacity in fractured rocks.

The need is apparent for measurements of physical and chemical properties at scales that will depict adequately the variations and features of a rock mass likely to be encountered in an actual repository. Regardless of sample size, laboratory measurements are very time consuming. Large specimens consume enough time and facilities to make numerous measurements impractical. Consequently, "scaling up" to more realistic dimensions can be performed, given reasonable limitations of time, manpower, and experimental facilities, only at the expense of a statistically representative data base. Limitations for obtaining precise data on physical and chemical properties at realistic scales are primarily time, money, and desired confidence levels, not the lack of conceptual experimental designs or instrumental techniques.

<u>Format of Data Presentation</u>. The suggested format for presenting information on rock properties information includes a listing of each of the properties as functions of rock type, lithologic properties,

temperature, pressure, ground-water chemistry, and source of data. Reasonable variations of the parameter values should be included in the listing as functions of both instrument uncertainties and stratigraphic-structural uncertainties. Cross sections of the site showing the geometric distribution of each property will also be prepared. A detailed text will include description of the samples analyzed, the in situ test facility, the reasons for choice of the site for the test facility, experimental designs, measurement techniques, theoretical relationships among the properties, and a general assessment of risks to containment failure due to physical and chemical properties. The text will also provide documentation of all programs and codes used to calculate the time histories of the thermal, mechanical, and chemical effects from emplacing heat generating wastes.

Estimated Resource Requirements. The resources required for characterizing physical and chemical properties depend on the degree of precision desired for large-scale natural rock masses. Assuming that 4 years' operation of an in situ test facility will provide adequate information to permit repository construction, pre-construction characterization of physical and chemical properties (including laboratory study) will require about 7 years and 20-30 million dollars following selection of a Potential Site. About 80 percent of the resources are required for construction and operation of the test facility, not including excavation of the repository shaft; the remainder for laboratory studies, primarily before construction of the in situ facility.

Geologic History

Geologic Factors. An understanding of geologic history could help in the prediction of geologic events that may adversely or beneficially impact radionuclide containment in a geologic system surrounding a repository.

In geologic time, changes in the lithosphere occur so slowly or at such infrequent intervals relative to the time span of concern to waste management, that the likelihood is extremely low that ambient containment conditions in a deep mined repository would be significantly altered by natural geologic processes. Nonetheless, study of potential geological changes and their likely impacts on repository containment is warranted, because the long times required for isolation of radioactivity from the biosphere make such changes conceivable, albeit unlikely. The study of geologic history and its extrapolation to the future is the only means for evaluating potential geologic change.

Characterization Methods. The method best suited for predicting geological events that may potentially impact repository containment is a combination of deterministic and probabilistic approaches.

Deterministic predictions require extension of processes posited by a geological cause-and-effect model that explains the distribution and relative timing of past events. This approach requires that the modeled processes, including any spatial migration, will continue into the future. It is thus based on an understanding of the cause-and-effect relationships among driving forces for geologic change, such as plate tectonics and isostasy.

Probabilistic approaches to geological prediction are based on (1) an ability to quantitatively date past events, and (2) the assumption that processes responsible for the past events are distributed randomly in time and space and will remain spatially unchanged in the future. This approach can be effectively applied to areas as small as 1000 square miles. As the area of concern for probability calculations increases, the physical significance of the results diminishes because parameters are averaged over a larger area. Consensus about the results is influenced by the degree of uncertainty associated with the measured or inferred ages assigned to past events. The assigned ages, in turn, are dependent on the degree of stratigraphic conformity, the accuracy and precision of radiometric dating, the number and distribution of datable features, and, for the last million or so years, the availability of geomorphological information that can be correlated with glacial advances or pluvial climates.

The deterministic approach should be used to define a general set of processes expected to act on broad regions in which a repository might be located. A historical synthesis should be submitted for extensive peer review to individuals from a broad spectrum of the geological community in order to derive a historical model that has broad professional support. Then, probabilities, in terms of statistical recurrence intervals, should be calculated for discrete events such as fault movements, volcanic eruptions, and seismic ground motions that may affect repository containment. The calculated probabilities should then be interpreted in light of the deterministic model to ascertain whether or not the probabilities based on stochastic assumptions overestimate or underestimate the likelihood of occurrence of the events in question at a particular site. These interpretations should again be submitted for extensive peer review.

Methods to obtain useful geologic information, other than that provided by stratigraphic, structural, or hydrologic studies, include deep geophysical surveys such as magneto-telluric soundings, and teleseismic delay measurements to evaluate geothermal gradients and their relationships to crustal stability in the site region; radiometric dating of additional intrusive and extrusive igneous rocks, spring deposits, vein fillings along faults and fractures, and buried and surface soil horizons; and seismic monitoring, both regional and micro.

Limits to Characterization. The limits to understanding geologic history and, further, of extrapolating geologic change into the future are the limits of human imagination and logic. By its nature, knowledge of geologic history is not, nor can it be, empirical. Geologic history is conceptualized by piecing together empirical observations obtained by study of stratigraphy, structure, hydrology, and rock properties. The observations are presumed to reflect conditions and processes that prevailed in the past for which much of the evidence has been destroyed. Conceptualization of the historical framework is an attempt to minimize inconsistencies between this largely obscured data set and the geological and physical laws.

Study of geologic history is conceptual, subjective, and requires a difficult intellectual exercise involving time spans that are disproportionate to anything existentially meaningful. Gaining a consensus about geologic history among geologists depends on the temporal and spatial scale of concern; the finer the resolution in time and space, the more elusive consensus becomes. For regions of 10^4-10^5 square miles, general consensus about tectonic forces may be obtained among most geologists, especially for stable regions. For smaller scales and more tectonically active areas, a consensus about deterministic models is difficult to achieve.

Format of Data Presentation. The suggested format for presenting geological history includes (1) a list of the radiometric ages of individual geologic features (volcanoes, faults, soil formation, etc.) and their distance from the repository site, (2) probability calculations for disruptive events as functions of magnitude and square miles centered around the site, and (3) a general text explaining the probability calculations, outlining the regional deterministic geologic model, describing the overall geologic history, and assessing the potential for disruption of repository containment posed by natural geologic processes.

Estimated Resource Requirements. The estimated resources required to obtain an understanding of geologic history and its projection into the future are in large part provided by stratigraphic, structural, and hydrologic characterization activities. However, the acquisition of information from the deployment of a seismic monitoring network, seismic data analysis, some radiometric dating, and deep geothermal surveys requires additional resources. The additional activities are estimated to cost 1-2 million dollars, depending on the complexity and recent geologic activity of the site. The minimum time required for seismic monitoring is 2 years. The other activities can be conducted concurrently with stratigraphic, structural, and hydrologic work. Peer review of deterministic models and probabilistic analyses is considered incidental to data gathering and is not assigned a direct cost.

Mineral and Energy Resources

Geologic Factors. Mineral and energy resources are those naturally occurring minerals that are both useful to man and commercially exploitable. They are significant for site characterization because the presence of such deposits could affect current land use, and, more importantly, exploration for such deposits by future generations might result in an inadvertent intrusion of the containment system. To assess resource potential, one can measure the geochemical concentration of individual elements and compounds.

Characterization Methods. Methods best suited for characterizing and evaluating the potential for present and future natural resource development are:

- Field mapping;
- Laboratory analysis of drill-core and geophysical logs;
- Evaluation of concentrations of individual elements and compounds relative to average crustal concentrations;
- Conceptual modeling of geochemical concentration mechanisms that have operated at the site; and
- Geophysical surveys.

The first three techniques are provided by activities for other aspects of geologic characterization, specifically stratigraphy and structure. If information obtained from preliminary geochemical assessments indicates that there is no likelihood for development of natural resources, no additional work will be necessary. If, on the other hand, there are indications of the presence of such resources, a more thorough evaluation of site suitability will be required.

Limits to Characterization. Characterization of mineral resources is not dissimilar in methodology from that used to characterize rocks that are barren of such deposits. Many of the same limits outlined in foregoing sections apply to the characterization of mineral resources. However, resource characterization is also constrained by our inability to predict which materials might be valuable for future generations, and the grades or mineral concentrations that could become economically exploitable. Another problem arises because mineral and energy resources are sometimes economically exploitable at depths greater than those studied during the characterization of a repository site.

Format of Data Presentation. Resource data will be presented in tabular, graphic, and narrative form, with an accompanying index map showing the locations of data points relative to the proposed site if potential resource deposits are discovered in the vicinity of the site. The tabular material will indicate each potential resource deposit, data sampling points, percentage (grade) of the deposit, depth of the deposit, and presently commercial grades for these depths. Accompanying graphs should present the same information, emphasizing variation in grade with depth throughout the resource-bearing interval, and the history of grades and depths exploited in the past. A detailed text will describe a geochemical model that accounts for the concentration of the deposit, the methods of sampling and analysis, the relation of the grade of the deposit to its average crustal concentration, and the potential for future mineral exploitation.

Estimated Resource Requirements. Manpower, time, and fiscal resources required to characterize and evaluate potential resource development will depend on whether or not any resource deposits are discovered during stratigraphic characterization. If needed, additional characterization to make this determination may require up to one year and from 0.5-1 million dollars. Eighty percent of the total costs will be required for drilling and the remainder for laboratory analyses and economic assessment.

Sequence of Characterization Activities

After selection of a Potential Site for detailed characterization, the objectives of geological investigations change. The objective of providing information to allow identification of favorably appearing sites is superseded by that of providing increasingly detailed information about a particular, selected site. The geological data that are gathered must eventually be of sufficient quantity and quality to satisfy a licensing agency, the geological community, and the public at large regarding the potential of the geological environment of the site and its environs to adequately contain emplaced radionuclides. Each of these audiences will perceive somewhat differently the problems of defining the term "adequately contain." Therefore, geological site characterization activities must be conducted in a sequence and manner that allow periodic review of findings by all interested parties.

The time required to achieve comparable levels of confidence about each of the factors described in the foregoing sections makes it desirable that characterization activities be conducted in parallel. In general, however, it is anticipated that studies of regional hydrology and rock properties will require more time than the other activities. Preliminary results might indicate that one or more features of the geologic system pose a special problem in terms of the ease with which they can be characterized or of their relation to repository containment. In either case, the sequence of work must be modified to give higher priority to the resolution of those special problems. Such emphasis on especially significant factors, if required, provides two advantages:

- Interested parties can review at an early stage the issues that have the greatest potential for disqualifying a site; and
- The chances are minimized for unnecessarily expending funds for characterization activities at a site that may later be disqualified.

Those factors which might prove most significant must be determined on a site-by-site basis and cannot be specified before selection of Potential Sites, at the earliest, and probably not until after preliminary site characterization work has been conducted.

Regardless of the relative site-specific significance of each geologic factor, certain steps toward achieving adequate characterization will generally be followed. Preliminary field mapping and geophysical work will be required to identify the approximate boundaries of the emplacement zone and to aid in location of an initial exploratory drill hole. The objectives of the initial drill hole are to verify the existence at appropriate depths of a suitable host rock or rocks, to identify any obviously unacceptable hydrologic condition in the emplacement zone and associated rocks, and to provide cores for the initial laboratory analyses of site-specific physical and chemical properties of these rocks.

Assuming favorable results from the first hole, commitment to an expanded exploration program is required. Seismic and electrical geophysical surveys will be conducted on a closely spaced grid that encompasses the entire emplacement and surrounding buffer zone. A seismic monitoring net will be established around the site. Field mapping will concentrate on identifying stratigraphic, structural, and hydrologic features in sufficient detail to permit three-dimensional digital modeling of the systems. Design, construction, and instrumentation of a generic rock-properties test facility may, if required, be performed at a site as representative of the potential host rock as possible; otherwise, such a facility will be deferred until the construction phase is authorized.

It is assumed that such test facilities will be constructed and operated independently of individual site characterization activities. However, the needs for (1) generic data upon which a judgment about the suitability of a site's target host rock can be made, and (2) available design and measurement techniques for an in situ facility at the time of shaft construction, may require experimentation in a facility away from the site and prior to shaft construction. However, because it is assumed that a limited number of test facilities of this type will provide sufficient background information for designing and operating in situ facilities in a variety of potential host rocks, construction of these facilities is not considered an essential element of the site characterization process.

A regional drilling program will be implemented to identify hydrologic conditions throughout the site's ground-water basin, with special emphasis on the area between the site and places of discharge. Geochemical analyses, including isotopic dating, will be made on a comprehensive suite of rock and water samples to support interpretations of geologic history and mineral resource potential.

Additional exploratory holes will be drilled into and beyond the target emplacement zone after evaluating detailed geophysical and field mapping data and considering preliminary engineering design studies not addressed in this report. These studies need to be considered in order to enhance the prospects that holes drilled into the site can later be used for access, ventilation, or emergency escape shafts, thus minimizing the number of site penetrations which will eventually need to be sealed.

The geological objectives of these holes are to confirm and (or) modify the three-dimensional stratigraphic, structural, and hydrologic conditions represented by the digital model; to provide additional cores for laboratory study of rock properties; and to provide facilities for subsurface geophysical surveying and hydrologic testing.

After the data from the second drilling phase have been evaluated and appropriate modifications made to the integrated digital model of the site's geologic, hydrologic, and appropriate physical-chemical properties, a geological site characterization report will be prepared. This report will include a prediction based on the digital model of the anticipated transport of radionuclides from the repository, assuming no changes in the geologic-hydrologic setting and complete dissolution of the waste form immediately after repository closure. Additionally, the effect of certain potential tectonic and climatic events on radionuclide transport should be calculated. When the report is submitted for extensive review prior to publication, it will also contain the geological information needed to apply for a license to construct a repository.

Assuming that no unacceptable impediments to waste isolation are identified in the report or during its review, the main emplacement shaft, horizontal exploratory core holes into the emplacement zone, and a rock properties test facility in the host rock will be constructed. A heater array simulating the thermal output density of the waste to be emplaced and an extensive monitoring instrumentation net will be deployed in the test facility to verify and (or) modify conclusions based on the results of a surrogate test facility about host rock response to emplaced waste. The horizontal core holes will be drilled along the trend of selected design drifts to provide an empirical data base for the assessment of the in situ three-dimensional stratigraphic, structural, and hydrologic conditions of the host rock. Cores from the holes will be analyzed in the laboratory to evaluate the adequacy of the predicted rock properties throughout the emplacement zone.

After construction authorization, the main drifts will be excavated, providing the opportunity for inspection and mapping of rock conditions. Additional horizontal and (or) vertical core holes can be drilled into the actual emplacement sites and rocks surrounding the emplacement zone for final confirmation of stratigraphic and structural conditions. Operation of the in situ test facility will continue during construction to provide longer-term data for verification of rock response models.

All information from the construction phase of characterization will be integrated into a final characterization report. This report will be submitted for review, will be published, and will serve as the geological input for a final license application to operate the repository. Assuming concurrence by the regulatory agency about site suitability, it is anticipated that an operational permit will be granted and that the objectives of the site characterization will have been fully achieved. After waste emplacement begins, monitoring of the effects of repository operations will supersede characterization, per se, although any new drifts, core holes, or shafts will be mapped for geological properties to assure that no unanticipated site conditions are left unevaluated. A summary of activities associated with site characterization is shown in Table 3.

Table 3.—Summary of activities to be considered during site charecterization

	Geologic Factors	Characterization Methods	Limits to Characterization	Format of Data Presentation	Estimated Resource Requirements
Stratigraphy	Lithology: distribution, facies, unconformities, mineralogy Fossils (depositional environment) Rock Properties	Field mapping Laboratory analyses Drilling Core & log analyses Geophysical surveys Isotopic dating Conceptual modeling Digital modeling	Extent of outcrops Structural attitude and complexity Subsurface penetrations Contrast in properties Previous knowledge Geologic history	Maps Stratigraphic sections Stratigraphic fence diagrams Digital models Text	$5M, 2-4 years in relatively simple environments $10-15M, 3-6 years in relatively complex environments
Structure	Dip, strike, folds, faults, joints, foliation, macro-texture, intrusive bodies, alteration and mineralization zones	Field mapping Core & log analyses Geophysical surveys Conceptual modeling Isotopic dating	Extent of outcrops Structural attitude and complexity Subsurface penetrations Contrast in properties Previous knowledge Geologic history	Maps Structure sections Rose diagrams Histograms Text	$2-3M, same time as for stratigraphy
Ground-water Hydrology	Stratigraphy Structure Porosity Potentiometric surface Hydraulic conductivity Topography Climate Mineralogy Water quality Water use	Field mapping Geochemical analyses Core and log analyses Hydraulic testing Isotopic dating Conceptual modeling Matrix modeling Static water level measurements	Geologic environment Structural complexity Subsurface penetrations Existing data Hydraulic measurements	Potentiometric maps Hydrologic cross-sections Flow models Computer codes Text	$10-15M, 3-5 years in relatively simple environments; $15-30M, 5-6 years in relatively complex environments; $2-5M for regional hydrology
Surface-water Hydrology	Surface drainage net Stream stage Sediment yield Topography Climate	Mapping Laboratory analyses Conceptual modeling Matrix modeling Stream gaging network	Short documentation period Stage measurements Sediment yield measurements	Maps Tables Graphs Text	$0.5M, 2 years
Physical and Chemical properties	Thermal conductivity Thermal diffusivity Thermal expansion Young's modulus Poisson's ratio Critical strength Bulk modulus Sorption	Laboratory tests In-situ tests Digital modeling Conceptual modeling	Scale factors Heterogeneity Complex interactions	Data tabulations Cross-sections Computer codes Text	$25-30M, 7 years
Geologic History	Sequence and results of past geologic events Seismic activity	Deterministic modeling Probabalistic calculations Seismic monitoring	Human imagination and logic Records: duration and gaps Uncertainties in dating techniques	List of geologic events Probability curves Text	$1-2M, 2 years
Mineral and Energy Resources	Presence of economically exploitable materials	Geochemical analyses Field mapping Core & log analyses Geophysical surveys	Subsurface penetrations Documentation history Future resource definitions and requirements	Maps Tables Graphs Text	$0.5-1M, up to 1 year

page 60 follows

RESEARCH AND DEVELOPMENT NEEDS

In general, Subgroup 1 feels that techniques presently available are adequate to proceed with identification and characterization of Potential Sites. However, improvement in techniques will be useful in achieving greater efficiency in site identification. The following suggestions for research and development are discussed according to the subdivisions of the Work Breakdown Structure in the "Earth Science Technical Plan for Mined Geologic Disposal of Radioactive Waste" TID-29018 (draft), January 1979.

WBS 1.0 Identification and Evaluation of Potential Geologic Environments

Investigations of the availability and usefulness of computer techniques for analyzing large masses of earth-science data would aid the process of screening Regions and Areas.

In the process of screening potential geologic environments, it would be useful to devise methods for dating old ground water (greater than 40,000 years) in connection with estimating the travel time of ground water to discharge areas. Research on the use of isotopic dating techniques involving ^{36}Cl, ^{85}Kr, and ^{14}C should be continued. Also, additional methods could be investigated including rates of helium accumulation, uranium disequilibrium, and changes in the optical properties of amino acids.

WBS 1.4 Candidate Host Rock

In view of the anticipated need for numerous repository sites, research should continue on the evaluation of the properties of various potential host media.

WBS 2.0 Site Characterization

WBS 2.2 Hydrology

A major difficulty in characterizing the hydrology in the vicinity of a repository site is in measuring hydraulic conductivity (intergranular and fracture) in porous media of low permeability. These measurements are needed to determine hydraulic gradients and rates of ground-water flow from which could be derived radionuclide transport rates from the repository to areas of discharge. In general, in situ measurement factors controlling ground-water flow in media of low permeability have not been made routinely. According to Bredehoeft et al (1978), relevant variables can be measured in the laboratory, although such measurements commonly vary by one or more orders of magnitude from those obtained through in situ tests. Furthermore, the problem is compounded by the large number of variables that must be measured to describe the transport process through fractured porous media of low permeability. Among these variables is the geometry of the network of fractures including the orientation and size of fracture apertures. Empirical data on flow through fractured media need to be collected and used in conceptual models.

Methods could be improved to aid in the process for measuring sorptive capacities of specific systems of rocks that occur in the field. Laboratory sorption measurements on representative rocks along the flow paths from each site should be made, particularly for the longest-lived radionuclides. These data would provide some basis for comparing site environments with respect to their potential for retaining waste radionuclides by sorption.

MONITORING NEEDS

Geologic and hydrologic properties determined during site identification and characterization could be monitored to detect any construction, operation, and post-closure effects of the repository. If monitoring systems are employed, they (1) should not be necessary to the functioning of the repository and (2) should not jeopardize the integrity of the repository. These prescriptions follow from the goal that surveillance of a repository is not a continuing requirement. As a corollary, neglect of such systems by future generations should be of no consequence. Indeed, the decision to maintain or discontinue a monitoring system must be theirs; this generation can only offer one. Although a monitoring program is not a technical requirement for waste isolation in a mined repository, an opportunity is available to ascertain whether or not the predictions of repository performance are valid.

A survey and periodic resurvey of surface elevations over a repository could reveal earth movements due to repository mining, repository operation, and hydrologic or tectonic activity. A hydrologic monitoring system can be used to determine whether or not the ground-water flow system including its chemistry is, indeed, functioning as predicted. Systems to monitor rock temperature, deformation, water chemistry, gaseous emanations, and radiation may be desirable (temperature sensors, extensometers, etc.), but the life expectancy of such instruments is short and, with today's state-of-the-art, would require hard-wire telemetry, which might preclude their use because they could jeopardize the repository's integrity.

After a repository is decommissioned, some post-closure monitoring could be employed for an indefinite future. This monitoring would be, for the most part, a continuation of operational monitoring. The details, however, cannot be specified now because the capabilities of monitoring systems that will be developed between now and a time that may be no earlier than the year 2050 cannot be anticipated.

Hydrologic monitoring may continue almost undiminished from the operational phase inasmuch as the more serious long-term concerns for a repository are concerns over the transport of radionuclides by ground water. The hydrologic monitoring might consist of periodic measurement of water levels and sampling of ground water in open boreholes outside and down-gradient from the disposal area.

In general, geologic monitoring is concerned primarily with detecting variations in geologic properties that would be indicative of potential releases of radioactivity, whether the variations were caused by natural geologic events or by the presence of the repository.

SUMMARY OF ESTIMATED TIME, MANPOWER, AND FISCAL REQUIREMENTS

As indicated in the foregoing text, the level of effort expended in arriving at Potential Sites increases, as Provinces, Regions, and Areas respectively, are characterized and evaluated. Table 4 summarizes these increases for a hypothetical "average" site or land unit. The estimates presented in Table 4 are based on the collective judgment of Subgroup 1 members in terms of 1979 dollars and are presented only to indicate a general order of magnitude for characterization costs. Actual costs for individual characterization activities may vary considerably from these estimates and depend primarily on the nature of major geologic uncertainties to be resolved for each particular land unit.

A hypothetical exploration program for identifying and characterizing twenty-six Potential Sites throughout the nation is schematically diagramed in Figure 3. The cumulative professional manpower requirements for this hypothetical program shown on Figure 4 are based on the single-site manpower estimates of Table 4. Drilling and other field-support costs are included in the total dollar estimates of Table 4, but are not included in Figures 3 and 4.

Figure 3 suggests the magnitude and flexibility of the site identification program outlined in this document. The flexibility arises from the number of Regions, Areas, and Potential Sites that are identified as geologically favorable but are held in reserve or "banked" as a result of the screening process. In addition, this program allows for the identification and characterization of alternate Potential Sites from which a subset can be chosen for licensing proceedings. Twenty-six nationally distributed, characterized sites were thought sufficient to satisfy the NEPA requirement for selection from among several alternatives within each of about five to eight national waste management regions, consistent with IRG recommendations. This figure is not to be interpreted as a guideline for the desired number of Regions per Province, Areas per Region, etc., but only as a general illustration of the overall screening process and its potential magnitude and flexibility. The temporal distribution of professional manyear requirements shown on Figure 4 could be significantly altered by adjusting the timing for sequential initiation of screening activities in the provinces, delaying the selection or subsequent characterization of various land units within one or several

Provinces, or by deferring site characterization until a selection of sites for licensing is made. No cost estimates were made for characterization activities during the construction and operation phases of repository development but are believed to be less than 5 million dollars.

Table 4.--Estimated time, manpower, and fiscal requirements*

Activity	Method	Average Time	Total Professional Manyears	Cost in Millions
Designation of Provinces	Delineation of broad geologic features	1 month	0.5	.040
Characterization of Provinces, subdivision into Regions, recommendation of Regions for further study	Review and compilation of existing data	6 months	6	.500 (per Province)
Characterization of Region, subdivision into Areas, recommendation of Areas for further study	Review and compilation of existing data	6 months	8	.600 (per Region)
Characterization of Area, recommendation of Potential Sites	Preliminary field work, lab work and review of existing data	2 years	20	5 (per Area)
Characterization of Potential Site	Detailed field work lab work	5 years	100-200	30 (per site)
Characterization of Candidate Site	Subsurface exploration and in situ testing	3 years	60 120	30 (per site)
Licensing documentation	Data compilation	2 years**	20	1.5 (per site)

*Time estimates are for actual work time only and do not include times required for negotiations, administrative review, and placement of contracts
**Will overlap characterization of Candidate Site

Figure 3.--Magnitude of a program for identifying and characterizing 26 hypothetical Potential Sites in the conterminous United States.

EXPLANATION

SYMBOLS

- Province
- Region
- Area — Land units recommended for further study
- Potential Site
- Candidate Site

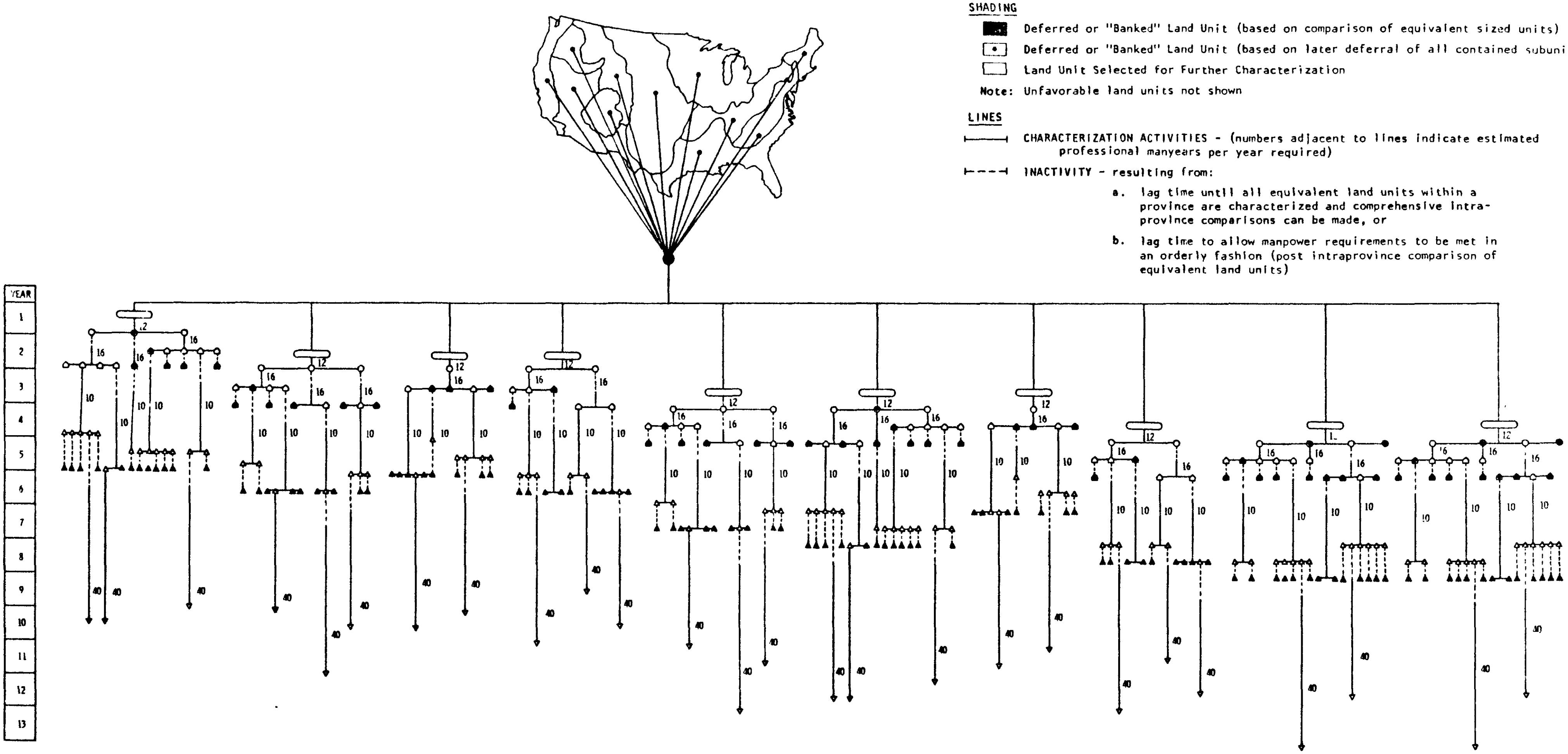
SHADING

- Deferred or "Banked" Land Unit (based on comparison of equivalent sized units)
- Deferred or "Banked" Land Unit (based on later deferral of all contained subunits)
- Land Unit Selected for Further Characterization

Note: Unfavorable land units not shown

LINES

- CHARACTERIZATION ACTIVITIES - (numbers adjacent to lines indicate estimated professional manyears per year required)
- INACTIVITY - resulting from:
  - a. lag time until all equivalent land units within a province are characterized and comprehensive intra-province comparisons can be made, or
  - b. lag time to allow manpower requirements to be met in an orderly fashion (post intraprovince comparison of equivalent land units)



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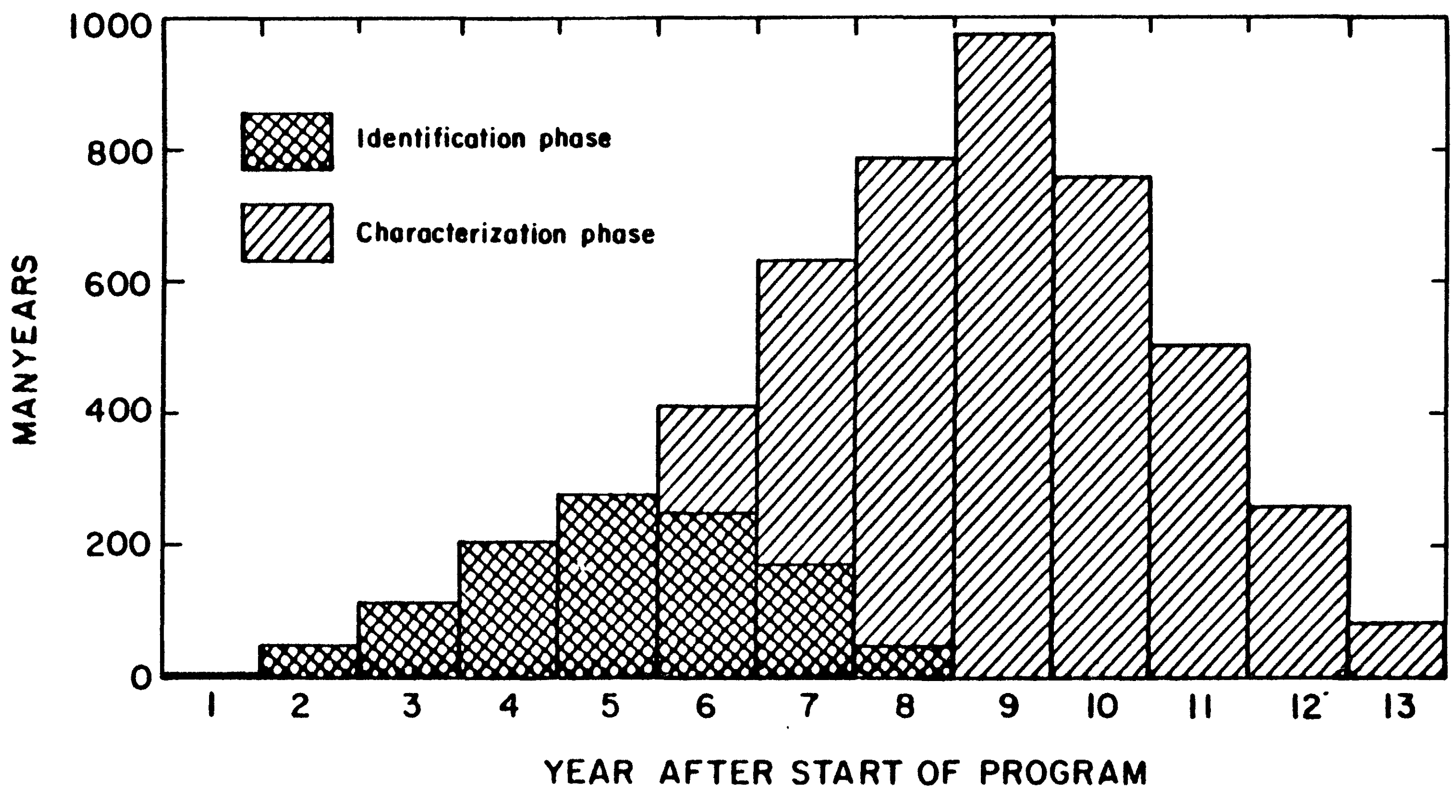

Figure 4.--Professional manpower requirements for a program for identifying and characterizing 26 hypothetical Potential Sites in the conterminous United States. (See Figure 3)

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GLOSSARY OF ACRONYMS

BWIP	Basalt Waste Isolation Project
DOE	(U.S.) Department of Energy
ESTP	Earth Science Technical Plan
IAEA	International Atomic Energy Agency
IRG	Interagency Review Group
NAS	National Academy of Sciences
NEPA	National Environmental Policy Act
NNWSI	Nevada Nuclear Waste Storage Investigations
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
NWTS	National Waste Terminal Storage (Program)
ONWI	Office of Nuclear Waste Isolation
ONWM	Office of Nuclear Waste Management
OWI	Office of Waste Isolation
TID	Technical Information Document
USGS	United States Geological Survey
WBS	Work Breakdown Structure
WIPP	Waste Isolation Pilot Plant