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ADDITIONAL MEDIA STUDIES FOR SITE SUITABILITY CRITERIA

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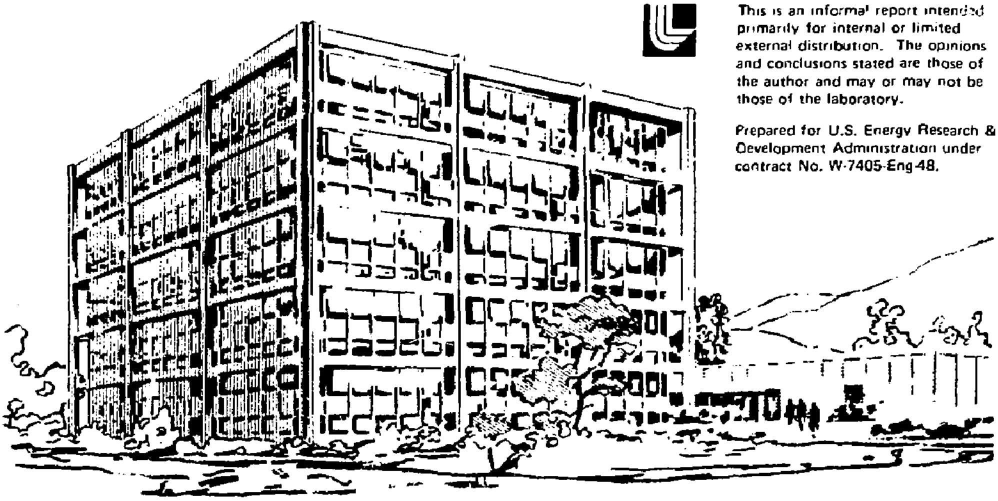

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INTRODUCTION AND SUMMARY

Site suitability studies at LLL to date have considered repositories in bedded salt and shale. The models have been varied to include a number of dimensions, parameter values, histories, and potential failure modes. These model studies have enabled us to provide preliminary site suitability criteria based on parameter sensitivity calculations and to begin uncertainty analyses.

Inasmuch as in situ tests are either underway or planned for the near future in other geologic environments in the United States, and since these environments may be recommended as waste repositories, work should begin immediately to produce results for these environments that are similar to those we have for the bedded media. Once the necessary data are available and the models developed, advanced analyses can be conducted in parallel with those on shale and bedded salt.

In this report we consider domed salt, basalt, and crystalline rock, comparing these three media with each other and with bedded salt and shale. Comparisons are made on the following basis:

1. The estimated level of effort required to develop models for these media that are similar in quality to those now available for bedded salt and shale. The models must therefore consider regional and local migration of wastes, recharge of the repository, dissolution, and other special effects.

2. Our present state of knowledge about the important physical and chemical properties of these media and the estimated level of effort necessary to develop data bases for each that are comparable to the data base we currently have for bedded salt and shale.

3. An evaluation of each medium as a suitable repository environment. The evaluation is based on construction costs, colocation of other resources, availability of potential repository sites, retrievability of stored wastes, and suitability of physical and chemical properties.

We have reached two principal conclusions on the basis of this study.

1. The funding necessary to bring our understanding of domed salt, basalt, and crystalline rock to a level comparable to our current understanding of bedded salt is estimated to be $1457K, $813K, and $1742K, respectively, for the three media. In each case, roughly 75% of the effort would be devoted to model development and analysis, 25% to data base development.

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2. Basalt and crystalline rock are about equally suitable as waste repositories in terms of all criteria except the availability of potential repository sites, where crystalline rock has a clear advantage. Domed salt should yield substantially lower construction costs than basalt or crystalline rock, but it is inferior in the categories of colocated resources and waste retrievability, and probably suitability of chemical and physical properties.

The funding estimates reflect not only the effort and time required for each medium study, but also the probable DOE schedule for experimental pilot plant work and for potential repository development. The studies should begin simultaneously, allowing them to be completed in the order: basalt, domed salt, crystalline rock. Hydrology studies and systems model development will be an extension of work either already completed or in progress at LLL. If studies of other environments and media become necessary, they can be made in the same way.

MODELING EFFORTS

INTRODUCTION

In this section, we discuss the effort required to bring the status of models for domed salt, basalt, and crystalline rock up to par with those for bedded salt and shale. We shall distinguish among models for regional migration, local migration, recharge/repressurization, dissolution, and special transport effects. Table 1 summarizes our findings for comparing the models needed for each new medium with the model available for bedded salt. We estimate the order of increasing modeling difficulty to be basalt, domed salt, and crystalline rock.

TABLE 1. Modeling efforts required. The table entries have the following meanings: (1) BSM indicates that the model developed for bedded salt can be used with only parameter changes (2) BSMM indicates that the bedded salt model can be used with slight modifications, and (3) NM indicates that a new model must be developed.

Model Area	Domed Salt	Basalt	Crystalline Rock
Regional Migration	BSM	BSM	NM
Local Migration	NM	BSMM	NM
Recharge	NM	BSMM	NM
Dissolution	BSM	BSMM	BSMM
Special Effects	NM	BSM	NM

BASALT

The modeling of basalt is in many ways similar to bedded salt since both are layered systems. As a result, the modeling of basalt will require the least effort. Parameter changes will be necessary and some structural changes in flow-path models may be needed for both local and regional migration. In addition, some effort may be required to model the hydrology of fracture systems that become progressively less permeable with increasing depth. Fracturing around underground openings may be different from that in salt or shale, depending on the mechanical characteristics of the rock and the mining methods used. In shafts and other vertical openings the fracturing and sealing characteristics can be expected to be highly variable because of the contrasting nature of the basaltic flows and the fractured and softer interflow material.

models for basalts and the other media will be used to investigate the consequences of the many release modes also common to bedded salt and shale repositories, such as shaft and backfill failures, fractures, faults, and borehole penetrations.

The generic basalt model will have geologic, hydrologic, and transport characteristics similar to those of the bedded basalts in the Columbia River basin and the Snake River plain.

DOMED SALT

The major modeling effort for domed salt is focused on local migration. Regional-migration modeling will be similar to that of bedded shale with a few parameter adjustments.

Our current data indicate that there would be essentially no flow paths out of an unflawed repository in a salt dome. This is due to the extremely low permeability of salt. Thus an unflawed flow model is unnecessary. Primary concerns about a salt dome repository center around flow pathways such as those caused by thermal gradients, molecular diffusion, salt dissolution, and the failure of shaft sealing. Additional modeling will include hydrologic investigations of thermally induced convective flow through rock of very low permeability, the opening of flow pathways by salt dissolution, and the movement of water and waste into a much more permeable sequence of sandstones and shales.

CRYSTALLINE ROCKS

Intrusive crystalline igneous and metamorphic rocks occur in a variety of geologic and topographic settings. These include the southeastern U.S. piedmont, the northern New England states, the areas of low relief in the Canadian shield province of northern Michigan and Minnesota, the small mountainous plutons of southern Nevada, and the Sierra Nevada batholith. Hence there are many kinds of hydrologic regimes and flow paths.

Water flow occurs through pervasive fractures or through more localized fault and shear zones, rather than through the rock matrix itself. Generally permeability decreases with depth until at some point it is essentially nil. Water content and flow velocity also decrease with depth within a system hydraulically connected to the near-surface water table. New hydrologic and flow-path models must, therefore, be developed to reflect these conditions. Initial models of many crystalline rock environments will show them to be clearly unsuitable for waste repositories. The most difficult problems will be with the more uniform environments where low flow rates and heat-induced convection must be modeled. Depending on the size of the area to be modeled, the frequency of fracturing, and the detail desired, a simple model may be applicable, in which water flow is analogous to the matrix flow in sedimentary rocks. A much more complex model will be needed where the size, spacing, and orientation of fractures are important. Different models will be required for calculating flow close to the repository and for recharge.

Retardation by ion-exchage or other surficial processes will depend on the areas of the exposed joint surfaces. This is true to a lesser extent in other jointed media, but in crystalline rock, where all flow is through fractures, surface area will have to be specifically considered. The simple retardation relationships now used for granular media are not applicable.

Construction-induced fracturing and problems with seals must be specifically modeled because of the different mechanical characteristics of crystalline rock, but conditions will be much more uniform than in basalt.

AVAILABILITY OF DATA

GENERAL REQUIREMENTS

The data base required for modeling includes the several types of geologic information that appear in Table 2. These data include the dimensions and geometry of the medium being modeled, the chemical environment, the hydrogeology, and the physical properties of the rock, both for the repository area and for the surrounding region. Pertinent physical laws, mathematical formulations and methods of analysis are important items in the data base.

Much information of this type is available from studies related to fuels, minerals, and civil work. Other necessary information specific to waste disposal has been and is being developed by DOE contractors and by researchers in several foreign countries.

It should be emphasized that much of the data and theory derived from laboratory experiments and from calculations are only first approximations. In situ underground experiments and measurements will be necessary before we can construct models that can be used with a high degree of confidence. Many of the parameters and processes must be site specific.

Dimensions and Geometry

The data must include accurate specifications of the waste disposal site. Geometric details include the attitudes and dimensions of joints, shears, faults, and any other features that may affect the performance of a repository. Knowledge of these parameters depends on the degree of exploration and the complexity of the geology. Knowledge at large depths is particularly dependent on exploration for water, fuel, minerals, and civil construction.

Chemical Environment

The chemical environment is described by all the parameters that might affect the types and rates of chemical reactions. The availability of chemical data is variable, and most have been obtained in geologic environments that may not be wholly relevant to nuclear waste disposal studies. Quantitative data about the behavior of dilute solutions of radionuclides in groundwater and about their reactions with rocks in natural underground environments are generally not available. In situ underground measurements will be required to reduce the uncertainties due to this lack of data.

Table 2. Data Requirements for repository modeling.

Dimensions and Geometry
Area
Thickness
Planar structures
Surface topography
Joints, shears, faults
Chemical Environment
Rock composition
Fluid composition
Rock/fluid/waste interaction
Eh and pH
Temperature and pressure
Wetted surface area
Water flow rate
Hydrogeology
Rock transmissivity (permeability)
Rock porosity
Rock fluid content
Rock specific storage
System pressures
Flow rates
Flow paths
Physical Properties
Strengths
Elasticity
Plastic behavior
Thermal conductivity and diffusivity
Specific heat
Thermal expansion
Temperature-dependent strengths

Hydrogeology

Hydrogeology data are gathered from a variety of borehole tests and geophysical measurements, and from laboratory experiments. In addition to information about the rock itself, these data include the pressure field in three dimensions and any available information about flow rates and flow paths, including the locations and rates of recharge and discharge. Availability of these kinds of data depends on the extent of exploration for and production of water, gas, and oil, and the distribution of civil works. Because many of these activities are either medium specific or limited in depth, the available information may not be representative of potential waste disposal sites. In general, though, a large body of data is available.

Physical Properties

Physical properties are particularly important when modeling design variations and nearfield thermal effects. Many of the mechanical data and the techniques used to analyze them have been extensively developed for mining and civil works. Thermal responses are not so well known and are peculiar to the problems of waste management. These data are being assembled by DOE contractors. Here, as in other areas, both mechanical and thermal properties need to be studied in situ with designs like those that will be used in a waste depository.

Basalts

The basalts being considered for waste repositories are large sheets of volcanic origin, generally comprising a series of related flows that form an assemblage of considerable thickness. This type of environment is of limited distribution in the U.S.; the principal area is in the vicinity of the Columbia and Snake Rivers in Washington, Oregon, Idaho, and small parts of some adjacent states. The locus of thickest accumulation is in the Pasco Basin of eastern Washington, where DOE contractors are making intensive investigations and are proposing in situ tests in mined caverns. Other information has become available from the construction of dams and tunnels at the many hydroelectric and floodcontrol projects in the Columbia basin. Some waste disposal studies have also been made in the Snake River plain in Idaho at the Idaho National Engineering Laboratory (INEL). The basalts in the Washington-Idaho area are shown on Figure 1.

Dimensions and geometry are well known to shallow depths from civil works and from groundwater production. For greater depths, information is available from INEL and from the ongoing work in the Pasco Basin. In general, structures and stratigraphy are simple and quite uniform: not as simple as for bedded salt and shale, but considerably simpler than for salt domes or much of the crystalline-rock environment.

The chemical environment is known as far as rock chemistry and groundwater are concerned. Some of the rocks and soils in the Pasco Basin have been studied in the laboratory for reactions between waste and rock, but the *in situ* geochemistry requires more study. Additional information may come from the proposed Pasco Basin experiments.

Hydrogeology data are probably adequate for preliminary model studies. Some water-well information and new drill-hole information from the Pasco Basin extend our knowledge to repository depths. Some extrapolation from other environments should be adequate to fill the gaps until more detailed exploratory results are available.

The physical properties and behavior of the rock are well known, with an adequate preliminary data base from power and flood-control projects. Additional laboratory measurements from deep test holes in the Pasco Basin are now being made under DOE contract. Most of the construction data are from relatively shallow depths, so they must be used with caution. In basaltic environments particularly, mechanical properties are different at greater depths because of (a) the lack of weathering typical of shallow unsaturated rocks, (b) the closing of joints under pressure, and (c) the action of precipitating solutions.

DOMED SALT

A great deal of information has been compiled on salt domes. The data come from explorations for oil, gas, and sulfur, from the production of mined and brine salt, and from the construction of storage caverns both here and abroad. DOE contractors continue to fill the information gaps important to nuclear waste studies, and *in situ* electric-heater experiments have begun at the Avery Island salt dome in Louisiana. The information base on salt domes is, in most cases, equal or superior to our information on shale and bedded salt. Radiation and heat effects in salt are better known than in any of the other rock media. The distribution of U.S. salt domes is shown in Figure 2.

The dimensions and geometry of salt domes are complex, because of the dynamic nature of dome emplacement. On the other hand, salt domes have been studied extensively, so many details are known, and a generic set of parameters can be established. Unfortunately, many features are site specific, so a generic model is not as applicable as it might be for bedded salt; assessment of a specific site will demand very detailed knowledge of the site. Specific structural details are currently being measured, and leveling and tiltmeter studies are being made by DOE contractors to determine the dynamic behavior of salt domes.

The chemical environment is, in general, well understood from commercial activities in and around salt domes. Dissolution phenomena are well established from solution mining and from operations to form storage caverns. As in other environments, details of *in situ* waste/water/rock reactions are not well known.

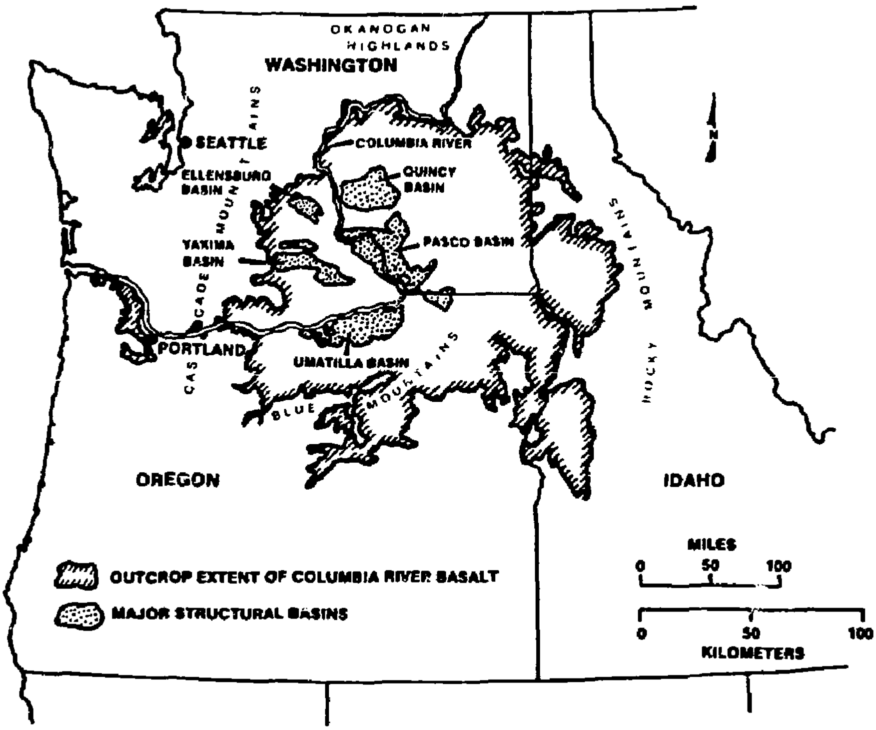

FIGURE 1. Location of Columbia River basalts.

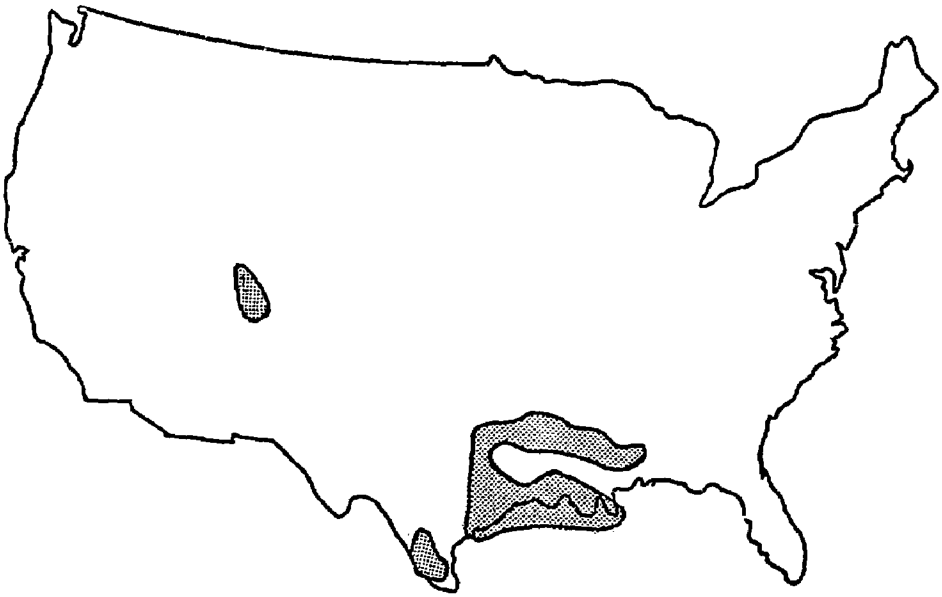

FIGURE 2. Location of salt domes in the conterminous U.S.

Hydrogeology in and close to salt domes is now the subject of studies under DOE contracts. Flow measurements in salt are difficult, and more field tests with improved methods will be needed to reduce current uncertainties. Hydrogeology in the shales and aquifers that surround salt domes is similar to (and as well known as) that in sandstone-shale environments. The data base is, therefore, adequate for a generic treatment of the salt dome environment.

Physical properties of salt have been extensively investigated, both for commercial purposes and for studies of nuclear waste disposal. American underground experiments for Project Salt Vault in Kansas, the on going tests at Avery Island, and the underground pilot plant at Asse, Germany, are specifically concerned with nuclear waste disposal. Some uncertainties exist about the migration of brine inclusions within the salt and about the effect of brine on rock strength, but these are being addressed by current research. The data base here is the best of all the media in its applicability to waste disposal.

CRYSTALLINE ROCKS

Crystalline rocks are here defined as those intrusive igneous rocks and high-grade crystalline metamorphic gneisses that are being considered for waste repositories. The general term is better than the commonly used "granite," which is a technical term for one specific type of igneous rock. Crystalline rocks are currently being considered for repositories in both Canada and Sweden. *In situ* experiments are in progress at Stripa, Sweden, and in the Climax stock at the Nevada Test Site in the U.S. Canada has begun site exploration for their preliminary experiments. Laboratory and theoretical work is in progress both here and overseas to fill the information gaps. Much of what we know is from mineral exploration and development, and from civil projects. The distribution of these rocks in the U.S. is shown in Figure 3.

The dimensions and geometry of crystalline-rock sites vary widely. In general, suitable sites are expected to have rather simple structures and uniform rock characteristics. Deep mines and some storage projects have penetrated to the depths of the proposed repositories, so a general three-dimensional picture is available. It should be noted that many mines and tunnels are located where they are because the rock is locally variable or has a complex structure, so data developed for other purposes must be used with caution in waste disposal studies.

The chemical environment in crystalline rocks is, in a large sense, not very complicated. The petrology of the rocks has been extensively studied, and water chemistry data are available where there are water wells, although deep wells in crystalline rocks are rare. On the other hand, relatively little work has been done on the reactions between waste and rock, and no good data are available on processes at great depths. Research to fill these gaps is planned.

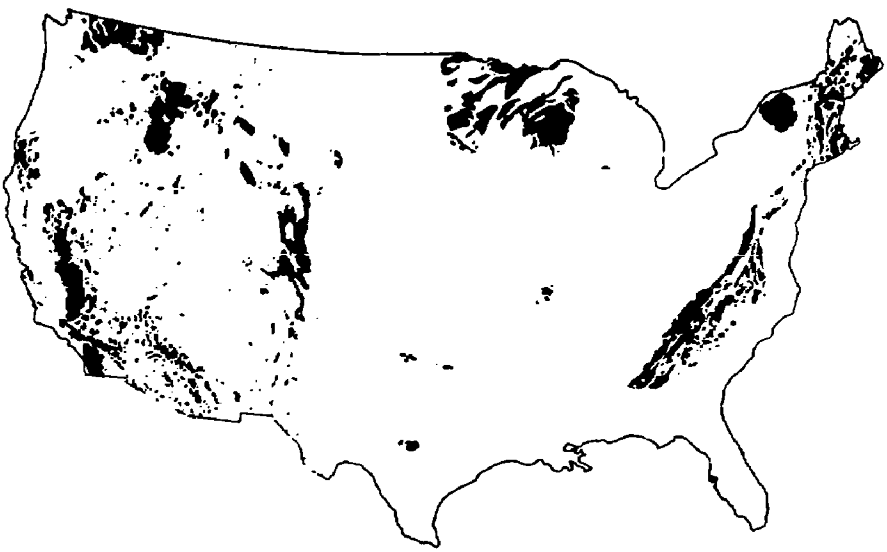

FIGURE 3. Distribution of exposed crystalline rocks in the conterminous U.S. (Includes gneiss and schist, holocrystalline intrusive igneous rocks, and Precambrian metavolcanic rocks but excludes low-grade metamorphic and Phanerozoic rocks.

Hydrogeology is well understood in shallow crystalline rocks, but a lack of deep wells means a lack of detailed information on the deeper flow regimes and on flow through fractures. Detailed studies and in situ experiments in Sweden will provide some of the needed information, as will some of the Canadian studies.

The physical properties of crystalline rock and its behavior as an engineering material are well known as the result of many studies and much experience in mining and excavation. The effects of heat on the mechanical properties are being studied by several DOE contractors, and heater experiments at the Nevada Test Site and in Sweden will provide additional information. Again, data from mining and civil works must be carefully evaluated since the rocks at many such sites may not be typical.

MEDIA FEASIBILITY

It is now possible to make only general statements about the relative feasibility of the various geological media as repository environments. These statements are the result of professional experience, and as such are qualitative and in some cases intuitive. More detailed study of the media will confirm or modify these judgments.

CONSTRUCTION COSTS

One aspect of repository development that will be important is the relative costs of construction and operation. Our estimate is that a repository in domed salt will cost about the same as a bedded salt repository. Because of the harder rock, as well as other factors, basalt and crystalline-rock repositories should be approximately two to three times as expensive as those in bedded salt. This factor is not directly related to the effectiveness of the repository as a barrier to radiological release, but it will be important in cost-benefit studies.

COLOCATION OF OTHER RESOURCES

Because future intervention by man might diminish the long-term effectiveness of a repository, it may be necessary to select repository locations that are not close to known fuel, mineral, or water resources. With respect to this factor, domed salt is the least favorable of these media because petroleum and fresh water are often associated with salt domes, and because of the salt itself. Domed salt is generally purer than bedded salt, thus salt domes are favored sites of salt mines, and in some areas, potash mines. Crystalline rock bodies are often associated with metal ore deposits. Fresh water resources occur only in the near-surface fractured zone of these rock bodies. The only resource of any significant economic value in basalt fields is the fresh water in the interflow aquifers.

AVAILABILITY OF POTENTIAL REPOSITORY SITES

Another important factor in the consideration of various media for waste repository development is the availability of potential sites. Salt domes occur in several parts of the U.S. including the Gulf Coast states and southeastern Utah. There are several hundred salt domes in these areas, but many have been developed for petroleum or salt resources. Other salt domes have been breached by natural processes.

Several kinds of rock bodies may be suitable for site development in crystalline rocks. The Canadian Shield area of the northcentral U.S. is a large area of metamorphic rocks with low topographic relief. Significant areas of crystalline rocks also exist in the Appalachian belt of the eastern U.S. Large batholiths such as the Sierra Nevada, Boulder, Idaho and Southern California batholiths are generally marked by high relief, although there are local interior drainage basins that and may be suitable for repository siting. Smaller intrusive bodies that may be large enough to permit repository location exist throughout the western U.S., especially in Nevada.

The U.S. contains only one large basalt province, the Columbia plateau-Snake River plain. This province, which covers several hundred thousand square miles, provides a large number of potential sites. Of additional interest are the large regions of the western U.S., especially Nevada and western Utah, that are covered by more local basalt flows as well as rhyolite flows and tuff deposits. Many potential sites are located in this environment.

RETRIEVABILITY OF WASTES

The feasibility of waste retrieval may also provide some constraints on the choice of repository site media. Granite, and other crystalline rocks, and basalt have the important advantage over domed salt that retrievability will be limited less by repository-waste interactions or by the physical properties of the rock. Retrievability in domed salt is a more complex problem because of heat-induced creep and the possible presence of corrosive brines.

SUITABILITY OF PHYSICAL AND CHEMICAL PROPERTIES

Table 3 summarizes our estimates of the suitability of these three media for repository siting, on the basis of eight important mechanical and chemical properties. We also rate the present level of knowledge about these parameters.

TENTATIVE RATINGS

Using the five criteria described above, we rate the three media as follows: Basalt and crystalline rock are about equally suitable as waste repositories in terms of all criteria except the availability of potential repository sites, where crystalline rock has a clear advantage. Domed salt should yield substantially lower construction costs, but it is inferior in the categories of colocated resources, and waste retrievability, and probably suitability of physical and chemical properties.

TABLE 3. Suitability of domed salt, basalt, and crystalline rock as repository media, based on their physical and chemical properties. The table also notes the current level of knowledge about each property.

Property	Domed Salt Suitability	Domed Salt Current Knowledge	Basalt Suitability	Basalt Current Knowledge	Crystalline Rock Suitability	Crystalline Rock Current Knowledge
Solubility	Very Poor	Good	Excellent	Excellent	Excellent	Excellent
Nuclide Retardation	Very Poor	Fair	Fair-Good	Poor	Fair-Good	Poor
Uniformity (Predictability)	Fair	Fair	Good	Good	Good	Good
Strength	Poor	Good	Excellent	Good	Excellent	Good
Fracture Potential	Excellent	Good	Poor	Fair	Poor	Fair
Thermal Conductivity	Excellent	Good	Fair	Good	Fair	Good
Thermal Stability	Poor	Fair	Excellent	Good	Excellent	Good
Chemical Stability	Fair	Fair	Good	Good	Good	Good