Title
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Publication Date
1990

LBL-28329

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

An Invited Paper to be presented at the International
High Level Radioactive Waste Management Conference,
Las Vegas, NV, April 8–12, 1990, and
to be published in the Proceedings

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Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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LBL-28329

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This work was supported by the Director, Office of Civilian Radioactive Waste Management, Office of Facilities Siting and Development, Siting and Facilities Technology Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

DYNAMIC USE OF GEOSCIENCE INFORMATION TO DEVELOP SCIENTIFIC UNDERSTANDING FOR A NUCLEAR WASTE REPOSITORY

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ABSTRACT

The development and safety evaluation of a nuclear waste geologic repository require a proper scientific understanding of the site response. Such scientific understanding depends on information from a number of geoscience disciplines, including geology, geophysics, geochemistry, geomechanics and hydrogeology. The information comes in four stages: (1) general regional survey data base, (2) surface-based testing, (3) exploratory shaft testing, and (4) repository construction and evaluation. A discussion is given on the dynamic use of the information through the different stages. We point out the need for abstracting, deriving and updating a quantitative spatial and process model (QSPM) to develop a scientific understanding of site responses as a crucial element in the dynamic procedure.

INTRODUCTION

Assuming that high-level radioactive wastes will remain on earth, it seems obvious that, to isolate them from the accessible environment against the hazards of natural disasters and the vagaries of humans and their institutions, the wastes should be entombed behind massive, strong and impermeable barriers. Intuitively, many persons would accept that entombing wastes behind hundreds of feet of concrete would render these wastes much less accessible than leaving them indefinitely in near-surface or open storage. They might actually consider that a thousand feet of concrete or more would provide acceptable permanent isolation.

The properties of materials are determined by their chemical composition and the geometry of their microstructure. Concrete is essentially a man-made rock. Most rocks are in fact significantly stronger than the best conventional concrete. It is not surprising then that deep geologic disposal in mined excavations has emerged as the favored method for isolating high level nuclear wastes worldwide.

Rocks differ from concrete in that they contain discontinuities on all scales from micropores and microcracks (which they share with concrete) to joints, fractures and faults of global proportions. The microscopic pores and cracks give rock and concrete their typical characteristics of weakness in tension, strength in compression and permeability to the flow of fluids. Unlike concrete, rock is available as extensive masses but these contain also much larger discontinuities than are found in concrete. These large discontinuities give rock masses properties that include essentially zero tensile strength, great strength in compression and permeability to fluids. In engineering practice, the low tensile strength of concrete is compensated by the use of steel to pre-stress concrete into compression. Gravity pre-stresses rock masses into compression. Conceptually then, concrete and rocks are very similar. We have experience of the behavior of concrete over thousands of years and knowledge of the behavior of rocks of up to billions of years. Consideration of these factors leads to the conclusion that deep geologic disposal is indeed the best practical way to isolate high-level wastes from the accessible environment.

INITIAL SELECTION OF A POTENTIAL REPOSITORY SITE

Some rock masses, on account of their composition and structure, are likely to provide much better isolation of nuclear wastes than others. How does one proceed to determine the suitability of a site for the geologic disposal of nuclear waste? Basically, the properties and behavior of a rock mass depend, like those of all other materials, upon its composition and structure and the tectonic stresses to which it is subjected and the nature, temperature and pressure of fluids contained in its discontinuities. These are precisely the characteristics of rocks that are studied by geologists. In fact, it is these factors that determine those engineering properties of a rock mass needed for repository design and performance analysis, such as the strength of the rock mass, its permeability to fluids, and the way in which the rock mass and contained fluids will respond to the excavation of the repository and the emplacement of heat-producing radioactive wastes. At the very crudest level, the selection of a rock mass as a host for a nuclear waste repository can be made using the existing geologic data base. Of course, other factors, such as other uses of the site and waste transportation strategy have to be considered also, but here we are concerned only with the suitability of the rock mass as a host.

For the process of repository design and performance assessment the characteristics of potential sites must be expressed in terms of the strength, permeability, and thermal conductivity of the rock mass, its mineralogy, the chemistry, pressures and temperatures of contained fluids, the state of stress, and tectonic setting as well as the variability of these properties from stratum to stratum and across the extent of the site. At every stage in the development of a repository from site selection to waste emplacement there must exist both a conceptual model of the structure and properties of the rock mass and of the design and performance of the potential repository. If the conceptual performance falls short of that required, the rock mass can no longer be considered as a potential site. The initial selection of potentially satisfactory sites can, therefore, be made on the basis of existing geological information.

SURFACE-BASED EXPLORATION OF A SELECTED SITE

However, geologic data bases usually contain information only on a coarse scale. The design and performance of a repository depend upon the properties of the rock mass not only on a geologic scale but on these properties on all scales down to the microscale. The behavior and properties of rocks on the scale of tens of millimeters can be measured rather precisely in laboratory tests. Information on scales between the geologic scale and laboratory scale can be obtained in the first instance by exploration using surface-based geophysical methods and boreholes. Geophysical measurements provide information about the geometrical arrangement of different structures and lithology that affect properties such as density, elastic moduli, connected porosity and pore fluids. Similar information can be obtained in greater detail for specific positions in the rock mass from measurements in boreholes and from experiments on borehole cores.

Information obtained in this exploration stage will both reinforce and change the original conceptual model of the structure and properties of the rock mass, and of the design and performance of the repository. Differences between this concept of the rock mass and the repository and the original concepts based on pre-existing data, provide important insight into the likely suitability of the rock mass as a potential host.

Surface-based exploration provides a much better concept of the site and repository than existed before. However, surface based exploration runs into diminishing returns long before all the answers to questions about the behavior and properties of the rock mass important to repository design and performance can be answered. Therefore, if after substantial surface-based exploration the amended concepts of the rock mass and of the potential repository remain viable, exploratory observations and experiments at repository depths become the most effective way of answering the remaining questions.

UNDERGROUND EXPLORATION OF A POTENTIAL SITE

The Exploratory Shaft Facility (ESF) provides direct access to a limited region of the rock mass, at depths of interest to repository design and performance. The location of the ESF should be based on a careful consideration of remaining questions. Using all the geologic information to date, where do most of the important questions and uncertainties lie? It would be a mistake to place the ESF in a region of the proposed repository of least uncertainty, because the information gained from the ESF observations and experiments does not necessarily apply across the whole repository.

As has been mentioned, the behavior and properties of a rock mass are determined by the chemical composition and geometrical structure of the lithology. Composition and structure are precisely the features that geologists are trained to observe. Careful geological mapping of the rock surfaces exposed during excavation is, therefore, the primary source of additional information. To some extent geological observations in the ESF will reinforce the previous concept of the behavior and properties of the rock mass and the repository design and performance and to another extent they will alter these concepts. Again important insights into the nature of the rock mass and repository design can be gained by carefully comparing current observations with previous concepts, taking particular note of any deviations between observations and concepts. In particular, those concerned with repository design and performance must evaluate continuously the potential effects of new observations on existing expectations of repository performance.

While it is true that, in principle, the behavior and properties of materials are determined completely by their composition and structure, the precise relationships between macroscopic properties important to repository design and performance, such as rock strength or permeability, and composition and structure are not known completely. Nevertheless, geological observations of changes in composition and structure are vitally important because such changes probably signal changes in macroscopic properties even if the precise relationship between composition, structure and properties are not completely understood. Furthermore, because geometrical structure changes with scale the resulting macroscopic properties also change with scale. Accordingly, it is necessary to make experimental measurements on a variety of scales from laboratory tests to that of the whole site. The ESF provides the first opportunity to conduct experiments and make measurements on the scale of the repository excavations.

The results of experiments and observations conducted in a strategically-located exploratory shaft facility will probably constitute the single most important step in the selection of a site, the development of a design, and an assessment of the performance of a nuclear waste repository. Direct observation and measurements in the rock mass at repository depths and large-scale experiments relating to full-scale repository performance provide the first truly direct and quantitative information on which the repository can be designed and its potential performance analyzed. An ESF will not be cheap but it will cost much less than the development of an inadequate site or of an inappropriate design. Sufficient time and resources must be devoted to the ESF both during the preparation period and during the actual construction not only to allow adequate and properly baselined observations, measurements and experiments to be completed but also to allow the results of these investigations to be evaluated fully and their effects on repository design and performance to be taken into account. The successful completion of ESF activities should provide great, but not complete, confidence in the rock mass, and allow the repository design and performance to be established. The ESF activities involve exploration of the unknown; some surprises must be expected. To maximize the return on investment, it is essential that there be a dynamic strategy for evaluating and directing ESF activities. Such a strategy must ensure that the implications of the new information are taken into account as they emerge, both with respect to the conduct and adequacy of the ESF activities as well as to the design and performance of the repository. To accomplish this, it is essential to develop a method for evaluating the results of surface-based and ESF activities in terms of ultimate repository performance and for reducing or revising these exploratory activities to answer questions and uncertainties that emerge from this process.

STRATEGY FOR USE OF ESF INFORMATION

A great deal of effort has gone into identifying the information that is required for repository design and performance assessment and into planning the means for obtaining this information from surface-based and ESF activities. No matter how carefully this has been done, exploration of the subsurface by surface-based methods or ESF activities will provide unexpected surprises. Therefore, it is essential to develop a dynamic strategy for optimizing both the collection and evaluation of information gained from exploration and for developing a scientific understanding of the site and of the repository. It would be totally unrealistic to expect that a prescribed plan of activities will generate all the data and knowledge that will be required for the design of a repository and the assessment of its performance. By definition, exploration involves the detailed investigation of the unknown. As new information becomes available this information must be evaluated in two respects. First, how is it likely to affect respository design and repository performance? Second, does the new information indicate that changes are required in the information needed or in the means of obtaining it. (Information needs may be found to be more or less than originally estimated).

These considerations clearly call for a dynamic strategy that involves explicit arrangements for the concurrent evaluation of information as it is collected and of the feedback of the results of these evaluations into the ongoing planning and conduct of surface-based and ESF exploration of the subsurface. Such a strategy is not only necessary but it can be expected to reduce the time and cost of either developing a site for a successful waste repository or of rejecting an unsuitable site.

The diagram in Figure 1 illustrates the principal activities and feedback loops required for an adequate and efficient process to generate the knowledge needed to assess the design and performance of a repository. It incorporates a number of specific activities that are essential to the successful utilization of exploratory data to evaluate site suitability and repository design and performance. These three components are inextricably linked to one another. One repository design could make a site suitable whereas another design could make the site unsuitable.

At every stage there exists a current base of data and technology. To make use of this information it is necessary to abstract from it a Quantitative Spatial and Process Model (QSPM) of the site and of the proposed repository. Without such a model no meaningful evaluations of the site for repository design and performance can be made. Conceptually such a model exists today and it must have been used in the decision to proceed further at a repository site. However, this model needs to be articulated in a real sense and in a very readily accessible format. In the past, this would have been done within a physical scale model using transparent and colored plastics to display the properties and spatial relationships between geologic structures and the repository excavation. Today, we can do this with computer graphics. This enables the model to incorporate much more information than could ever be done with a physical model. It also allows processes, such as fluid flow, to be incorporated in the model. Finally, computer graphics facilitate a dynamic model that allows changes in the properties, spatial arrangements and conceptual processes to be made in a dynamic sense as new information or scientific understanding becomes available.

The process of abstracting a QSPM from the data base will itself constitute a significant advancement in understanding the characteristics of a site and of the design and performance of a potential repository for that site. The process also constitutes a vital synthesis of data and an implicit evaluation of the site. Abstraction of the data and construction of the model must be a multidisciplinary process involving, at least, climatologists, geologists, geophysists, hydrologists, geotechnical engineers, and geomechanical engineers. The process is quite distinct from those of, as examples, planning and conducting site characterization, or repository design and performance assessment. Model construction and continued revision should be a critical parallel activity in addition to and using information from these ongoing activities. The process also raises vital issues of establishing interfaces between the disciplines in the process of building the model as well as those of establishing interfaces with parallel activities such as site characterization and repository design. What we envisage is a specific multidisciplinary team which would not be responsible for conducting activities at the site nor for building the data base—its only functions would be to abstract the QSPM from the data base and evaluate this model, and build a scientific understanding of the site and of the proposed repository.

The dynamic evaluation of the model involves three principal components: first, the formulation of computational models which may range in complexity from simple bounding calculations to comprehensive computer codes; second, the selection and revision of values for parameters that are needed to perform the calculations; third, clear identification of uncertainties in the formulation of the computational models, in the current values of the parameters, in the process models, and in the resulting estimates of repository performance. Within and between each of these three components exist also essential feedback loops. These three activities must also be interdisciplinary as is the formulation of the QSPM. Indeed, the construction and evaluation of the model and the development of scientific understanding are but two parts of one integrated activity. The most important part of these multidisciplinary activities concerns the interfaces that must be established between the different disciplines and between various components of the computational models. For example, how does one couple tectonics to hydrology or rock mechanics to waste package design? The answers to these questions of interfacing and coupling are neither simple nor obvious. Furthermore, these answers are likely to change through time as our knowledge of the behavior and properties of the site improves and as our understanding of the response of the ESF activities develops.

The abstraction and evaluation of the QSPM described above differs significantly in character from the process of site characterization and perfomance assessment that are already well-defined aspects of the national nuclear waste management program. On the one hand, site characterization and performance assessment are carefully planned deductive processes leading from the general, site data and explicit process models, to the specific repository performance. On the other hand, QSPM abstraction and evaluation are highly-intuitive, hueristic and inductive, proceeding from the specific to the general. A QSPM can be abstracted and evaluated at any stage from initial selection of potential sites on the basis of a pre-existing geologic data base to the final stages of repository closure.

There is another important aspect in which the formulation and evaluation of the QSPM is vital to success. In many respects, such as the generation of radioactive heat and the expectation of long periods of isolation, a geologic repository for high level nuclear wastes raises geoscience questions outside the realms of past experiences. These questions are not going to be answered satisfactorily by collecting a large set of quantitative data and analyzing it with computer codes. It is essential to develop a

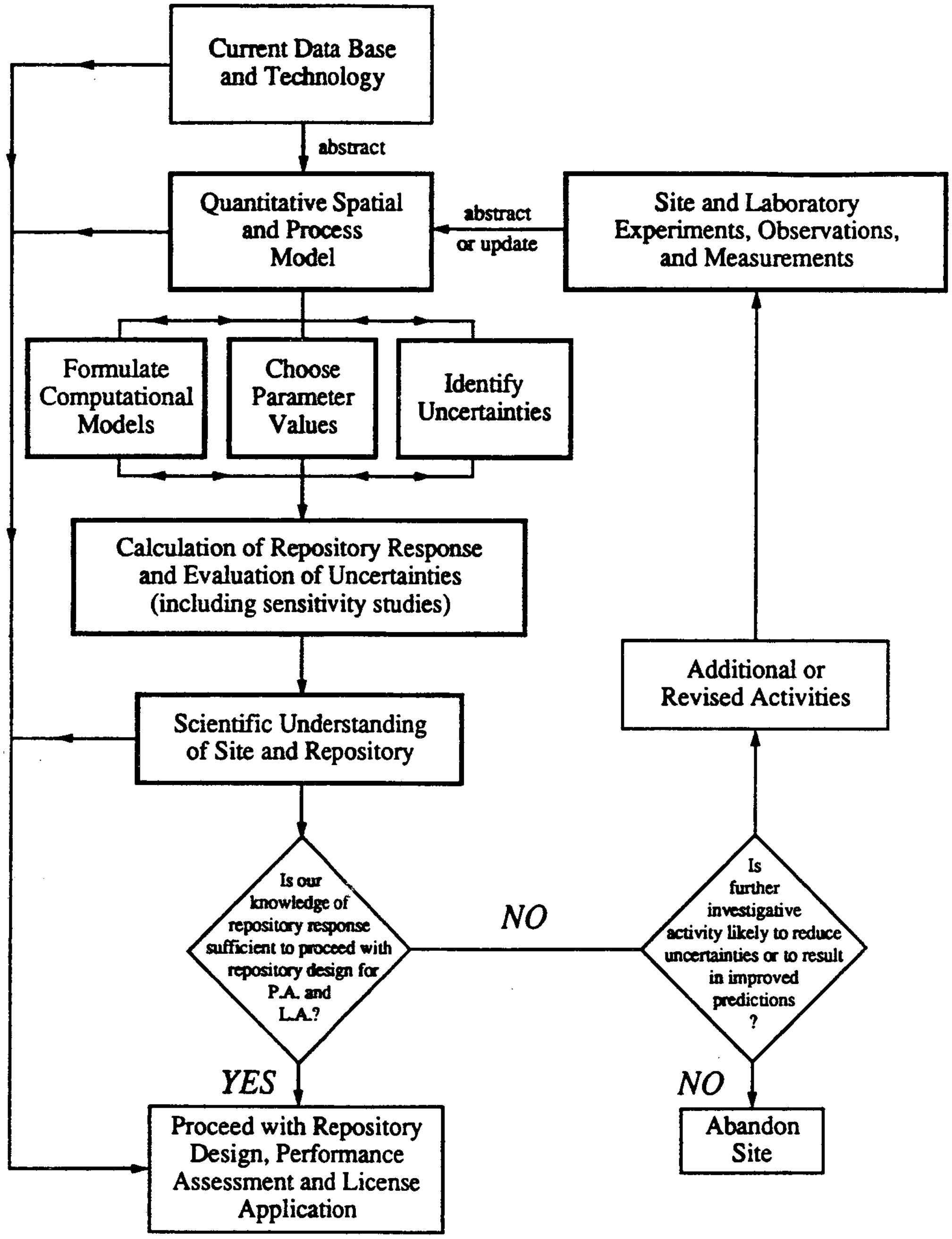

FIGURE 1. A dynamic strategy for evaluating geoscience data to develop a scientific undestanding for the development of a repository. (Items in the darker-lined boxes are discussed in this paper.)

scientific understanding of the site. This scientific understanding is something that must be nurtured and developed. It will grow out of a synthesis of both qualitative and quantitative abstractions as a result of site characterization and repository development and, most importantly, by means of multidisciplinary synergism. Such synergism does not occur with separate disciplinary teams. It requires a single, relatively small, multidisciplinary team. The most important aspect of this dynamic strategy involving the abstraction and evaluation of the QSPM is, therefore, the vehicle it provides for developing a scientific understanding of the site and of the repository, knowledge that cannot exist a priori.

Perhaps the single most important source of information and understanding will derive from abstractions concerning the response of the site to perturbations by, first, the excavation of the ESF facilities and, second, the development of the repository itself. It is extremely improbable that a scientific understanding of the site can be built upon a data base, no matter how extensive it may be, and computational models, no matter how comprehensive they are, alone. Science and understanding do not develop in that way. They develop as a result of in-depth study of careful observations and measurements of the response of the system to perturbations.

The ESF facility constitutes a significant perturbation of the site. For example, it creates a hydraulic sink down to repository depths, as will the repository. Therefore, one of the most fruitful sources of scientific knowledge about the site will be measurements of the response of the site to the excavation of the ESF. Such measurements would include changes in hydraulic head, changes in the degree of saturation, changes in air flow, and induced displacements and stresses in the rock. In principle, all of these changes could be predicted from the data base using appropriate models. In practice, the actual response is likely to differ from the initially predicted response, because our scientific understanding of the site a priori will be incomplete. Disparities between observation and prediction serve to highlight weaknesses in our understanding.

To observe and measure changes it is necessary first to know what the initial or baseline situation is. Establishing baseline conditions requires an extensive program of direct and remote measurements in deep boreholes. Direct measurements would include, for example, those of pore pressure and temperature, whereas indirect measurements would include seismic and electrical tomography between boreholes. Finally, it should be noted that our ability to measure changes in conditions, such as those brought about by the ESF, is much greater than our ability to measure absolute values. This fact further underlines the importance of measuring the effects of large scale pertubations. After all, the ability of a repository to isolate nuclear wastes from the accessible environment depends upon the response of the host rock to the perturbations brought about by repository excavation and waste emplacement.

All these activities take time and effort: to drill the boreholes and time to make the baseline measurements. However, these measurements are fundamental to generating the scientific undestanding of the site which is needed for the development of a satisfactory repository.

REPOSITORY DEVELOPMENT

Careful observations and measurements in connection with the ESF are likely to constitute the single most significant step in providing the understanding needed to develop a repository. However, the ESF comprises only a small fraction of the total area of a repository. Likewise, ESF observations and measurements will be made for only a few years before the development of a potentially satisfactory repository site begins.

Geological properties vary from one location to another in space. Furthermore, the processes of concern in the isolation of nuclear wastes occur over decades, centuries, and millennia. The excavation of the repository itself offers an important opportunity to extend observations and measurements at the site in space and time.

Certainly, measurements of the perturbation of the site within and around the ESF should be continued until the repository is closed. This will extend the duration of these observations from less than a decade to several decades. A careful program of observations and measurements within the repository excavations would extend the data base to the full extent of the repository and allow the perturbation of the site by the complete repository to be evaluated. In this latter respect baseline conditions established prior to the ESF activities provide the background against which the changes brought about by the complete repository construction can be compared.

Observations and measurements in the complete repository may differ in character and scope from those required in the ESF. Intense and detailed observations and measurements in the ESF will have provided the scientific basis for understanding the site and the changes that are expected to be brought about by the excavation of the repository and the emplacement of the waste. Observations in the repository excavations, such as geologic mapping, will establish the extent to which conditions throughout the repository are either similar to, or different from, those at the ESF. It is quite likely, indeed probable, that significant differences will emerge between the behavior and properties of the rock mass near the ESF and elsewhere in the whole repository area. (It would be equally important to demonstrate that no significant differences between ESF and the whole repository exist, if that was the case.) These differences may require further modifications of the repository concept to be made in order to achieve satisfactory performance. The movement of groundwater is central to the issue of satisfactory waste isolation. Groundwater saturation and movement are expected to be quite variable. It would be important to make measurements of saturation and flow, either directly or indirectly, throughout the repository excavations as a function of time as a result of excavation and waste emplacement. Such measurements can be compared with initial predictions and numerical simulations. Another important measurement for comparison with model predictions would be temperatures.

DISCUSSION

The process prescibed by the Nuclear Waste Policy Act and the pertinent regulations embodies a compelling logic that recognizes the uncertainty inherent in any major geotechnical enterprise. At each stage, the decision to proceed is contingent upon satisfactory information obtained in a preceding stage. This logic makes it essential to maintain the option to retrieve the waste up to the very last stage of repository development and waste emplacement. Indeed, experience with large geotechnical or mining enterprises has shown that it is necessary to anticipate that unexpected conditions may be revealed at any stage of the entire process. Figure 2 illustrates the interplay between the information available and the investment in repository development at every stage, from inception through waste retrieval or repository closure, as the case may be The magnitude of the investment in the repository increases at each stage as the uncertainties about the geologic environment and repository diminish with increasingly comprehensive knowledge about the site. The most expensive decision, whether to retrieve the waste or close the repository, is reserved for the end.

Initially, based on a concept of the behavior and properties of the subsurface system developed through surface-based exploration, a potential repostiory design is developed. If the potential performance of the proposed repository based on this initial concept of the subsurface sytem appears to be satisfactory, a considerable increase in the investment so as to develop the ESF is justified. The ESF allows the surface-based concept of the geological system to be checked by direct observation and enables measurements and experiments to be made to determine the behavior and properties of the rock mass pertinent to repository construction and waste isolation. Such experiments and observations could not be done from the surface. Undoubtedly, the additional information about the rock mass revealed by the ESF

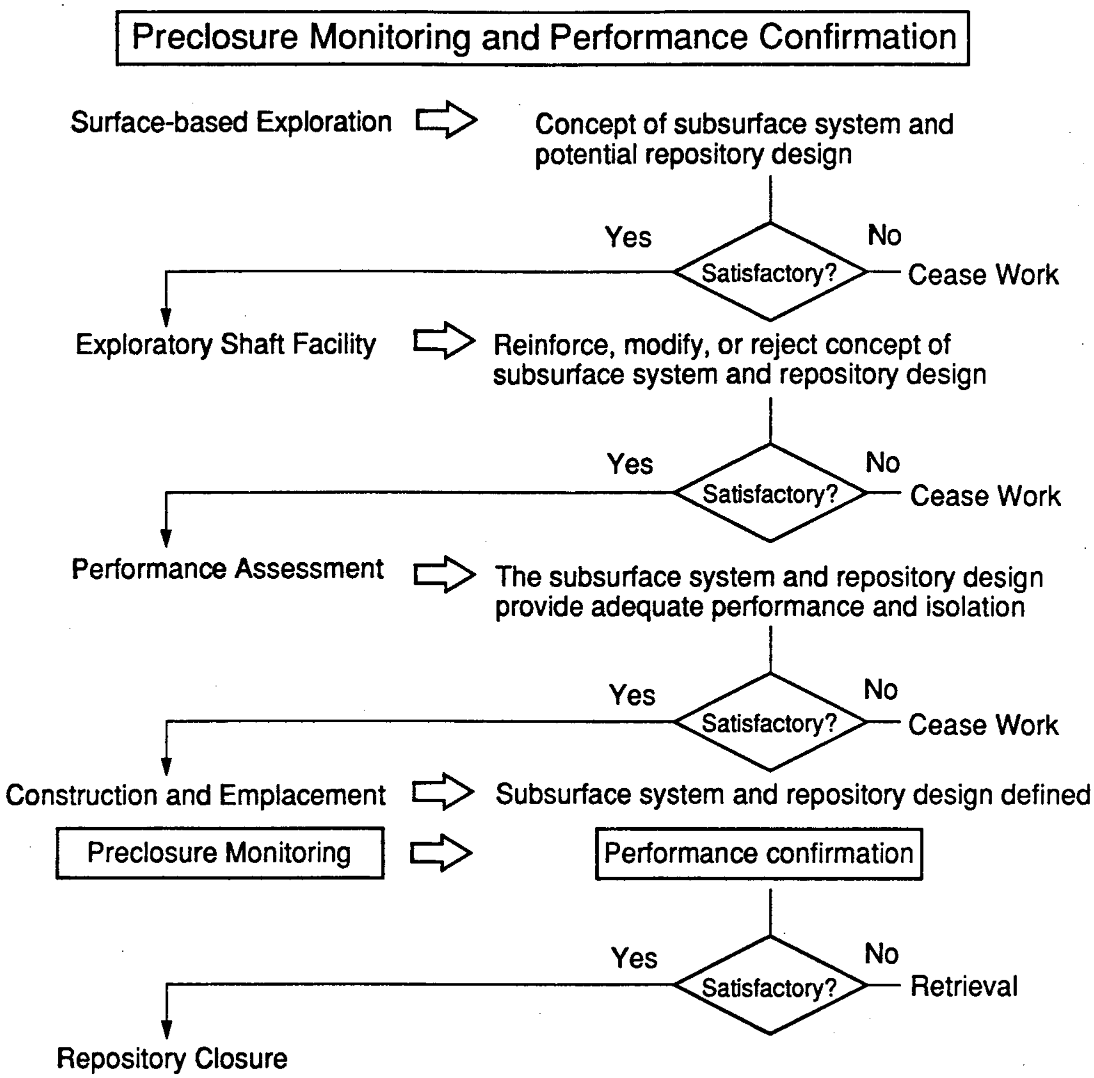

FIGURE 2. The step-by-step process in which increasing confidence in a site and the design and performance of a repository is matched by increasing commitments. XBL 892-7460a

activities will confirm some aspects of the original surface-based concepts and modify others. This leads to a more comprehensive and less uncertain concept of the subsurface geologic system and a modified concept of the proposed repository. If the performance of this modified repository concept is still satisfactory, the investment in the repository proceeds to the next, more costly, stage of repository construction and waste emplacement.

Just as the ESF observation and measurements are needed to provide the information on which to base the decision to invest in the costly stage of repository construction and waste emplacement, so is a program of preclosure monitoring and data analysis during construction and emplacement needed for the potentially even more costly decision of whether to retrieve the waste or close the repository. The magnitude of this decision (to retrieve the waste or not) must be based on unassailable evidence about the properties of the geological environment and the performance of the repository. In this context, preclosure monitoring assumes major significance in the logic leading to an informed and defensible decision that will have to be taken concerning retrieval, after an enormous investment in the repository has been made.

CONCLUSIONS AND REMARKS

The paper reviews the dynamic use of multidisciplinary site specific information to develop the scientific understanding needed to design and develop a nuclear waste geologic repository Never before in the fields of geosciences and geoengineering was there such a high demand placed on the site characterization and safety evaluation of the construction of an underground space. Such a demand requires carefully considered and dynamic use of site information as discussed above We classified the site information into four successive stages: (a) general regional geologic and geophysical surveys, (b) surface-based exploration and testing, (c) exploratory shaft facility testing, and (d) repository construction and testing. At each successive step the information is more specific and more comprehensive providing a steadily-improving scientific understanding for repository safety evaluation. Also at each successive step, a larger pertubation is imposed on the system, so that the system response would more likley show forth finer and maybe unexpected site behavior.

In order to study the system responses to the perturbations at the different stages, a carefully designed monitoring program needs to be established early with a proper set of baseline data and to be carried out consistently through the four stages, up to waste emplacement and repository closure. Such a program of pre-closure monitoring especially in the stages of exploratory shaft testing and repository testing (in the latter case including thermal perturbation from the emplaced wastes) may yield important and critical information for confirming performance assessment carried out at the earlier stages. These confirmation attempts may result in refinement of performance estimation or in the adjustment of further repository development and closure plans. In the extreme case, retrieval of wastes for alternative storage sites may be necessary. Note that this preclosure monitoring period beginning now until repository closure covers several decades, providing unique, site-specific, long-term observation data for performance assessment validation. All this means that proper multidisciplinary baseline measurements need to be carefully designed and implemented now, and that such monitoring be performed at every stage in a properly scientifically based (versus schedule-driven) manner.

In Figure 1, two parts of the dynamic use of site information are well recognized in the national program. These are site characterization (right hand side of the chart) and performance assessment (left hand side of the chart: three connected boxes on computational models, parameter values and uncertainties and the next box on calculations of repository response). However, two other elements in the chart represent the critical links that hold these two parts together and according to our realization they have not be adequately emphasized. The first critical link is the abstraction to arrive at a Quantitative Spatial and Process Model (QSPM). This is a scientific process whereby the multidisciplinary data from geological, geophysical, geochemical and hydrogeological observation are digested and assimilated into a comprehensive picture of the site. Such a scientific process requires an in-depth study and discussion of these data by a group of competent and experienced scientists to integrate all information into this QSPM, which will be updated as new information is obtained throughout the four stages of site information collection. The second critical link is the development of a scientific understanding of the site on which to base the evaluation of performance assessment. This is much more than making numerical predictions that satisfy specific regulatory requirements. As we are attempting to predict into thousands of years based on data which will not describe every micorscopic and macroscopic detail of the site discretely, confidence of our prediction cannot depend on the few calculated numbers with certain (or uncertain) error intervals, but must depend on a thorough scientific understanding of the site and repository. Such understanding should be documented and open to scrutiny by the scientific public. Eventually it is this understanding and acceptance by the scientific public that is going to convince the general public and ourselves of the probably safety of the repository we are developing.

The views expressed above are our personal interpretations of the scientific needs for the successful development of a geologic repository for nuclear wastes. We recognize that there are many regulatory and institutional requirements that must be met, which we are not qualified to address.

ACKNOWLEDGEMENTS

Reviews and comments from Drs. Joe Wang and Harold Wollenberg are gratefully acknowledged. The work was sponsored by the Director of Office of Civilian Radioactive Waste Management, Office of Facilities Siting and Development. Siting and Facilities Technology Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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