DEALING WITH UNCERTAINTIES IN THE DEVELOPMENT OF A GEOLOGIC REPOSITORY FOR HIGH-LEVEL WASTE

L.A. White, H.L. Bermanis, E.R. Wiot
Roy F. Weston, Inc.
Rockville, Maryland 20850

M.W. Frei
U.S. Department of Energy
Washington, DC 20545

ABSTRACT

A geologic repository combines a number of technologies in a unique way, must function over geologic time, and by its nature requires a level of understanding of subsurface conditions that is unprecedented. The uncertainties that derive from this are significant in terms of demonstration of repository performance in licensing. The Department of Energy is approaching the problem by 1) identifying the major areas of uncertainty and reducing those uncertainties through an iterative process of investigation, and testing; 2) anticipating irreducible residual uncertainties likely to remain due to practical limitations, and 3) developing and evaluating practical solutions for dealing with those irreducibles. A comprehensive site characterization program leading to prudent site selection coupled with a defense-in-depth approach to design is the major focus of the DOE effort to deal with those uncertainties.

INTRODUCTION

A geologic repository for high-level radioactive waste has some unique aspects that will result in uncertainties in demonstrating system performance. First is our inability to fully demonstrate performance through observation. Thus, the classical observational approach used by engineers can only be carried out partially and can only be used for some elements of the repository system. Secondly, geologic disposal will involve combining advanced technologies in a number of areas in a unique way. We have experience in each of these areas individually and thus we can draw on these experiences in other applications of those technologies. However, often when we combine known but different technologies in a new way, the constructed system very often does not initially perform as expected. The third unique aspect of repository development is that there will be an unprecedented need for site data. There will be a burden on the DOE to demonstrate sufficient understanding of subsurface conditions such that all the important issues have been identified. Data will be needed to characterize potentially adverse conditions for scenario development where there are known issues. Also, additional data may be needed to characterize barriers for waste isolation. There is a clear desire to know more about the site than has historically been needed for any other type of underground structure. However, there are practical limitations imposed by existing investigational tools and also by the need to limit subsurface penetrations so as not to impair the isolation capability of the site.

The uncertainties that derive from these considerations are very significant in terms of how they may affect the demonstration required to obtain a license. The uncertainty related to the first successfully manned moon mission was probably a comparable situation. However, if we had had to get a license to put a man on the moon, we may not have achieved it because of the problem of demonstration.

This paper identifies the major sources of uncertainties with respect to long-term safety, defines the approach the Department of Energy, Office of Geologic Repository Deployment, will take to reduce these uncertainties during repository development, and how it plans to deal with the residual uncertainties in preparation for repository licensing.

IDENTIFICATION OF MAJOR SOURCES OF UNCERTAINTIES

There are uncertainties in site characterization, and in predicting the effects of the emplaced waste on its surrounding environment and in their impacts on engineered barrier performance. There are also uncertainties in characterizing the effects of the thermal effects on ground water movement and radionuclide transport, and the ability to predict the future performance of the repository system over a period comparable to geologic time. Identification and minimization of these uncertainties is important in site characterization and to waste package and repository design particularly with respect to designing to minimize corrosion and leaching of the waste and minimizing radionuclide migration from the waste package.

Site Characterization

Uncertainties in the characterization of a waste repository site are primarily due to potential inaccuracies in site measurements, uncertainties in the interpretations of site-specific data and the interpolation, extrapolation, and analysis of such data, and finally uncertainties in our geologic, hydrologic, and performance assessment models. Key site parameters we are interested in, such as ground water travel time, must be measured indirectly and some factors, such as geochemical retardation, will be very difficult to measure using any technique. Also, because we cannot make as many measurements as we like, we will need to fill gaps in data using expert judgment and preconceived models of the site, and there will be uncertainties in these assessments. Much of our final description of subsurface conditions and results of performance assessment will be based on our conceptual model of the site. There will be uncertainties in the modeling because of our analytical limitations and also because all the data we collect will not likely fit that model. In a licensing proceeding it is likely our understanding of each of these types of uncertainty will have to be made explicit at least in the major areas cited above. We believe that early characterization of these uncertainties can help focus the development of site characterization plans and further R&D work needed to reduce these uncertainties to an acceptable level.

A major source of uncertainty in site measurements is in the quality and accuracy of data gathered. More data can always be gathered to characterize a site more precisely. However, if a specific site measurement used is not measuring representative conditions, the data may not accurately characterize that specific property. Also, the quality of data is very dependent on how it was gathered. Experience shows, for example, the quality of data in the geotechnical area is very investigator dependent. Having standard measurement procedures helps some, but there are practical limitations because such procedures have to allow for adjustment to suit site-specific conditions.

Uncertainty in the results of model calculations are due to inaccuracies in our models and the interpretaticn of results. Models provide a means to fill gaps in data and are used to theoretically derive other data. Often we forget the results cannot be any more accurate than the data input to the models and often we believe in our models too much. These uncertainties can be characterized using appropriate alternative models to develop confidence limits on a model, or by establishing probability distributions for input data and characterizing the uncertainty in the results using probability techniques.

There may be several models which appear to fit the available data and be appropriate for the calculation desired, but which give different results. There may also be a model available for a particular calculation which has been verified for a range of input data which falls outside or otherwise does not cover the available input data. Each case leads to uncertainties in the application of the model. Use of a particular model and extrapolation and interpolation of data is many times a subjective decision made by one or more experts in the area. Because experts may have differing views on the choice of model or use of a model outside its validation, there may be uncertainties in the results of the use of such models.

Waste Emplacement Effects on Engineering

Much of the uncertainty in predicting the performance of the engineering barriers, particularly the waste package, is due to the thermal and radiation effects which affect prediction of changes in temperature, stresses, fluid pressure and flow, and the chemical environment over time. In particular, there will be difficulties in the characterization of the waste package environment and thus predicting the life of the waste package and the rate of release of radionuclides.

The heat generated by the waste will result in a temperature gradient through the waste package and host rock, which in turn affect material stresses and ground water pressure, flow, and chemistry in the vicinity of the waste packages. There may also be chemical changes in the waste package and host rock. All of these considerations affect corrosion rates, leach rates, geochemical reactions, stress on the waste package, and radionuclide solubility and migration away from the waste package, in ways not fully understood. There will thus be uncertainties in predicting these reactions and therefore uncertainties in predicting repository system performance.

As with heat generation, radiation from the waste form can cause changes in material stresses and properties, and ground water characteristics. Such effects may include heat buildup in portions of the waste package or host rock which would complicate the effects of heat generation discussed above; and radiolysis of ground water and other materials in the vicinity of the waste package. Uncertainties in radiation effects therefore also have an influence on the ability to predict repository performance over long periods of time.

Thermal Effects on Ground Water and Radionuclide Transport

The temperature gradient extending from the waste emplacement area will affect ground water movement and the potential for radionuclide transport in what is often referred to as the disturbed zone. There will be uncertainty in predicting thermo-mechanical effects such as changes in the transmissivity of the rock mass with time and distance from the waste emplacement area due to thermal expansion and contraction. This will in turn affect estimates of the time it will take for repository resaturation after closure and the identification of preferred pathways for radionuclide transport. The temperature gradients will also result in thermal instability in the ground water thereby creating thermal pressure gradients due to buoyancy effects. Water may be present both in a fluid and a vapor state, thus severely complicating analyses of ground water movement. Also, the amount of free oxygen that will be retained in the water will be affected, and thus this will further complicate predicting geochemical retardation. These conditions, in combination, will be the source of uncertainties in the prediction of radionuclide transport.

Prediction of System Changes

Another area of major uncertainty is predicting changes to the geologic and hydrologic environment and the potential for man's intrusion on the repository, and engineered *barrier performance* over thousands of years. These types of assessments are much more tenuous, particularly as we extend our predictions out with time; but on the other hand, we are less and less concerned with predictions with time as the probability of the events becomes very small and as the toxicity of the waste significantly decays. There will be significant uncertainties nevertheless in characterizing scenarios and assigning probabilities to them.

DEALING WITH THE UNCERTAINTIES

The DOE Office of Geologic Repository Deployment is proceeding with the following approach to dealing with uncertainties in preparing for a license application for the first repository.

1. Reducing uncertainties to the degree practicable through the prudent choice of an exploration and testing program at each stage of repository development.

2. Anticipating irreducible, residual uncertainties likely to remain due to practical limitations in our measurement and testing capability, models, and limitation in engineering judgment; and

3. Developing and evaluating practical and cost effective solutions for dealing with the irreducible residual uncertainties early in the process.

REDUCING UNCERTAINTIES

Site Characterization

Much of the site uncertainty can be reduced by iteratively analyzing the source of uncertainties and by focusing the DOE program of investigation and testing in those areas. The DOE is planning to proceed in an iterative process of data collection and performance modeling to guide the site characterization effort and at the same time develop and validate models that reflect actual site condition. Preliminary site models and sensitivity analyses will be used to identify and prioritize the key parameters. This will help focus the site characterization effort on collecting data that can be used to define these parameters thus reducing uncertainties in them. Since these parameters "drive" the process, overall uncertainty will be significantly reduced. Performance models can be used as an aide to analyze and select methods for obtaining the data needed and they can be used to design site-specific tests. The applicability of tests will be assessed based on the representativeness of data that would be collected and the uncertainty that can be expected in the data. Uncertainties in terms of the validity and reproducibility of site measurements can be limited through sound QA procedures. Finally, by reducing uncertainty in the site data and models, the uncertainty in the performance assessment calculations will be subsequently reduced. This in turn ensures a better understanding of the site and thus increases the likelihood of selecting a site that has the least irreducible uncertainty.

Waste Emplacement Effects on Engineering

The results of site characterization work can also be used in establishing priorities for further R&D work in support of repository design. Efforts are underway to minimize uncertainties in predicting waste package performance. Tests will be performed during site characterization to more fully understand the effect of heat and radiation on the waste package environment. Also, tests will be performed on materials under anticipated repository conditions (chemical, pressure, temperature, radiation). Trade-off studies which will examine alternative system designs under those conditions will be done to optimize the barrier system. For example, providing multiple corrosion barriers provides diversity of barriers but produces more complex chemical reactions. An alternative approach would be to use fewer material types or components but to overdesign them, e.g., by adding sacrificial material or by adding leach or corrosion resistant material. Finally, options for controlling and limiting the thermal loading and radiation effects will also be evaluated.

Uncertainty can be further reduced by limiting the waste loading per waste canister, thus reducing the temperature changes within and around the waste packages. Uncertainty can also be reduced by including features in the design that enhance the local chemistry of the water and that favorably control local ground water movement that affects the amount of flushing and thus change in the local ground water chemistry with time.

Dealing with Thermal Effects on Ground Water

Sensitivity analyses will be performed to determine the key parameters affecting thermo-mechanical and ground water interactions that will control the rate of migration of radionuclides through the disturbed zone. These may include, for example, the initial hydraulic pressure distribution, the porosity of the geologic units, and their degree of saturation. During site characterization the DOE plans to conduct experiments that address coupling effects. Data gathered will help in our understanding of what the dependent and independent variables are so that we can reduce the uncertainties in prediction. New models will be developed and, in an iterative process, these models will be used to refine the site characterization process.

Uncertainties can also be reduced by controlling the average waste loading per acre. Uncertainties can be further reduced through repository design, operation, and establishing construction sequences that allow ventilating more waste heat during the initial period when the heat density is greatest.

Predicting Changes to System

DOE is working with the EPA and the NRC to place bounds on scenarios for repository performance assessments. Site-specific scenarios will be developed early to help focus site characterization plans. The uncertainties in such performance within those bounds can be dealt with both in site selection and design. Sites that are less complicated geologically and more stable can be more readily modeled. Also, the better our understanding of the site, the less uncertainty there will be in assessing engineering performance.

ANTICIPATING AND COMPENSATING FOR IRREDUCIBLE, RESIDUAL UNCERTAINTIES

There will be residual or irreducible uncertainties for any site. We need to anticipate what they will be early. These uncertainties are extremely important because the site must provide a substantial barrier on its own. DOE will not attempt to engineer a site to make it adequate. This approach is articulated in the DOE Siting

Guidelines. Thus, these uncertainties need to be understood in site selection.

Engineered barriers will be included as part of a defense-in-depth philosophy to ensure that there is reasonable assurance the EPA standard and requirements of 10 CFR 60 are met. However, there will also be residual uncertainties in demonstrating the performance of these barriers. The major difficulty in the engineering will be in isolating radionuclides that have a long half life which exceeds the time it would take them to reach the accessible environment. Currently we have very limited knowledge regarding the long-term performance of engineered materials. Also we will be faced with the difficult problem of predicting how these materials will degrade and thus the rate of release of radionuclides.

Site Characterization

The major area of residual uncertainty in site characterization will be in estimating geochemical retardation provided by the site. There will also be some residual uncertainty in estimating ground water travel times. These residual uncertainties about the site will be used to evaluate site suitability and to establish performance measures for the engineering so as to comply with NRC requirements. Also, site-specific requirements for the engineering and the likelihood of meeting the engineering performance measures will be factored into the site selection decision.

Engineering System

An important part of the engineering process will be to scope out and quantify the residual uncertainties centering around alternative design concepts. We want to be sure we are not substituting one set of uncertainties for another. There are known uncertainties and unknowns; i.e., we could have modelled the wrong problem. Thus, we must continue to be skeptical in this process to increase our knowledge of what may be unknown.

The major area of residual uncertainty regarding the engineering will be in predicting the ground water chemistry and its rate of movement around the waste packages. These factors affect canister corrosion, radionuclide solubilities and leach rates. There will also be residual uncertainty in the characterization of ground water flow in the zone of influence of thermal effects. This uncertainty can be compensated for in part by conservative design of the waste form, its packaging, backfill, and seals and, in part, by a defense-in-depth design approach.

PRACTICAL SOLUTIONS TO IRREDUCIBLE UNCERTAINTIES

A defense-in-depth approach would consist of providing a redundant barrier and/or multiple barriers that achieve the same objective but which function on a different principle. These concepts are what has traditionally been practiced in the engineering of complex systems in general and are used extensively in the design and construction of nuclear facilities.

For a repository, the waste package has the potential to physically hold radionuclides in the structure of the waste form, the solubility of the radionuclide complexes in the waste form provide a chemical barrier, the canister or overpack provides an initial containment by acting as a corrosion barrier, and the backfill material around the waste package provides another geochemical barrier.

A program of testing and evaluation of engineered components will begin with the site characterization process and be carried through to closure of the waste disposal facility. As site data is collected and we learn more about the site, this information will be factored into the engineering testing program so that more realistic tests can be run on the engineered barriers thus further reducing uncertainties. The objective should be to select alternative combinations that optimize performance and confidence in such performance at reasonable cost. In the early stages conceptual design concepts will be tested, and as the flexibility of design decisions become more and more restricted, more detailed aspects of design will be tested.

SUMMARY

In summary, DOE will take the following approach in dealing with uncertainties in the development of a geological repository for high-level radioactive waste.

1. Ascertaining where there are uncertainties, either in the characterization of the system or in the estimate of system performance;

2. Estimating the degree of those uncertainties in the areas identified, and quantifying them to the degree practical, even if this process is subjective in part or whole.

3. Reducing uncertainties through the prudent choice of an exploration and testing program at each stage of the development process.

4. Anticipating residual uncertainties likely to remain long after closure of a repository due to practical limitations, and engineering judgment;

5. Development of practical and cost effective solutions for dealing with residual uncertainties without being unduly restrictive or conservative; and

6. Evaluation of solutions through testing and observation during site characterization, construction and facility operation.