SYSTEMS PERFORMANCE ASSESSMENT FOR A YUCCA MOUNTAIN REPOSITORY*
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T. O. Hunter and F. W. Bingham
Sandia National Laboratories
Albuquerque, New Mexico 87185

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ABSTRACT

The development of a geologic repository must include evaluations to determine whether the repository system can satisfy the regulatory requirements for postclosure waste isolation. The Yucca Mountain Project of the U.S. Department of Energy (DOE) includes a performance-assessment program as part of this evaluation. This program focuses on developing and applying methods to determine the isolation potential of the unsaturated tuff at Yucca Mountain. The methods must be based on an understanding of the fundamental concepts of fluid flow, radionuclide releases from the engineered-barrier system, and radionuclide transport in unsaturated, fractured rock. They must be capable of addressing both expected site conditions and unexpected potentially disruptive conditions. They must ultimately be efficient enough to accommodate numerous parameters and their associated uncertainties in the development of the statistical representations that are necessary to satisfy regulatory criteria. The existing methods are based on the current information about the site but will ultimately be supported by data to be obtained during site characterization.

INTRODUCTION

The primary function of a nuclear waste repository is the long-term isolation of radioactive waste. The decision to begin construction or operation of a repository will depend, in part, on the results of a licensing process with the Nuclear Regulatory Commission (NRC) that must include an evaluation of the effectiveness of the repository system to fulfill this primary function. The Yucca Mountain site in southern Nevada is being characterized to determine its potential as a location for the nation's first civilian repository. This characterization program must ultimately provide analyses to determine the potential of a repository at this site to isolate nuclear waste. These analyses are typically called "performance assessments" and can include many types of evaluations. This paper will provide an overview for the systems performance assessment for the Yucca Mountain site that is a part of the current site-characterization program.

Total-system performance assessment can be simply defined as an evaluation of the performance of the system to meet regulatory requirements. The specific requirement addressed in this paper is the postclosure isolation of radioactivity, where postclosure refers to that time after permanent closure of the repository. Hence, we do not address evaluations of operational safety, radiological safety, or the performance of the repository and host rock during the time before closure. The system to be evaluated includes the site, the repository, and the engineered barriers associated with the repository. These total-system requirements are imposed by 10 CFR 60 of the NRC as expressed in the standards of the Environmental Protection Agency (EPA). These standards for postclosure isolation, in Subpart B of 40 CFR 191, address three basic concerns: (1) release of radioactivity to the accessible environment, (2) individual protection, and (3) groundwater protection. The concepts for total-system performance assessment can be explained by focusing only on the first of these concerns.

A simple concept for the repository system at Yucca Mountain is shown in Fig. 1. The site consists of bedded tuffs in which the water table lies between 500 and 800 m below the surface. The repository horizon would be located approximately 200 m above the water table and at least 200 m below the surface. The repository would consist of mined rooms over a region of approximately 7 km^2. Waste packages of either spent fuel or high-level defense wastes would be placed in the floor of the repository rooms. Access to the waste-emplacement rooms would be by vertical shafts to the surface and inclined ramps to the waste-handling facility in the repository-operations area. The performance of these combined features must be evaluated to ensure that isolation is provided.

Showing compliance with the EPA standard for release of radioactivity to the accessible environment primarily consists of providing a measure of the amount of radioactivity that could be expected to reach the accessible environment in a 10,000-yr period. The accessible environment is an envelope that surrounds the repository and consists of the earth's surface and a boundary below the surface that is 5 km from the region of waste emplacement. Stated briefly and with some oversimplification, this standard requires that the accumulated radioactivity reaching this boundary in 10,000 yr not exceed amounts specified. While this standard is currently being reconsidered by the EPA, it expresses an intent to restrict the radioactivity that could endanger future generations and is thus the focus of total-system performance assessment for the Yucca Mountain Project.

The approach for total-system performance assessment can be expressed by examining three basic features that make up the program: (1) the physical concepts and models that describe each individual element of the system, (2) the methods, based on these concepts, that can be used to predict radionuclide release, and (3) applications of

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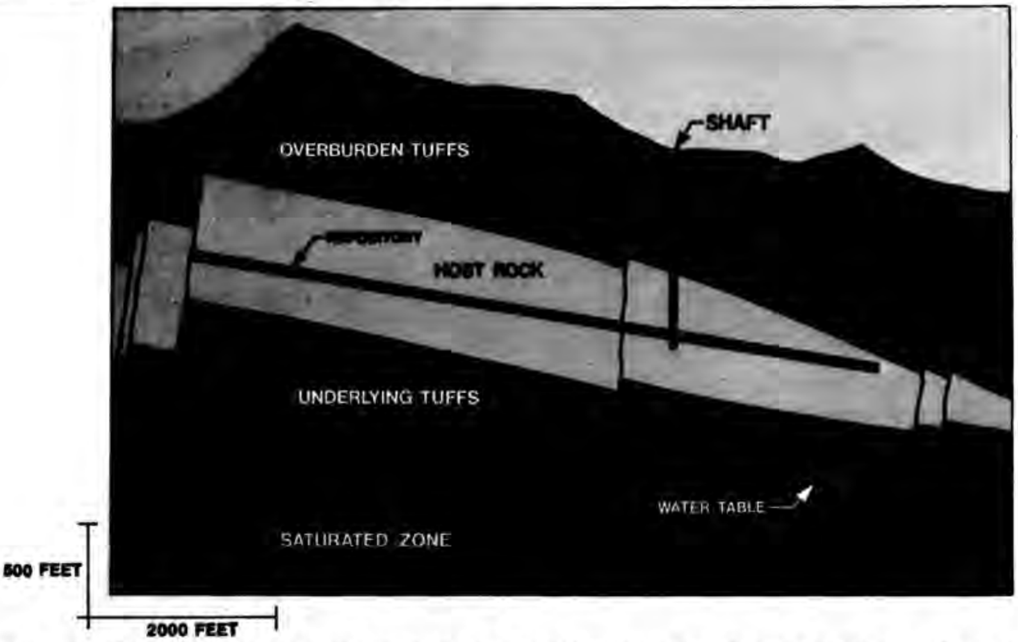

Fig. 1. An East-To-West Cross Section Through the Yucca Mountain Site, Showing In Simple Form the Major Features of a Repository System.

these methods. Subsequent sections explain each of these features.

PHYSICAL CONCEPTS AND MODELS

For a release of radioactivity to occur from a repository at Yucca Mountain, radionuclides would have to leave the engineered-barrier system and move through the mountain to the accessible environment. An important mechanism for the transport of radionuclides # i.e., their movement through the mountain # would be fluid flow: either as solids dissolved in percolating ground water or, for some nuclides, as gases or vapor. The assessment of releases, then, requires an assessment of three primary components: fluid flow in the rock units, radionuclide release from the engineered-barrier system, and radionuclide transport to the accessible environment. The performance- assessment program is developing concepts and models describing each of the components.

The development of concepts and models for fluid flow requires an understanding of the flow mechanisms that occur at the site. In particular, the models consist of mathematical descriptions of rock hydrologic and pneumatic properties, of the partitioning of fluid movement between the rock matrix and the fractures within the rock, the driving potentials for fluid movement, and the characteristics of fluid flow through the rock. The development of all these parts of the models is under way, and references to much of the work may be found in the simplified discussion in Section 8.3.5.12.1 of the Site Characterization Plan (1). Because ground-water flux in the unsaturated zone is of special importance to these models, the site- characterization studies will emphasize the dependence, if any, of this flux on climatic conditions and the infiltration and percolation rates in the mountain. The primary results that these models supply for use in the total- system performance assessment are fluid velocity distributions and saturation conditions throughout the mountain.

The concepts and models for radionuclide release from the engineered-barrier system are developed from the studies carried out in the program for evaluating the waste package and its environment (2). Estimates of the waste-package lifetime will rely on descriptions of the local environment and possible modes of degradation of the packages; estimates of the radionuclide release from failed packages will take into account the available inventory of radionuclides, the physical form of the nuclides, the solubilities of the nuclides, and reaction rates among the chemical species that are present near the waste packages. For the total-system assessment, the primary results of these models are source-term distributions: i.e., temporal and spatial distributions of radionuclide injection into the fluid-flow systems within the mountain.

The concepts and models for radionuclide transport are closely related to the models for fluid flow and for release from the engineered-barrier system. Beginning with the velocity and source-term distributions from those models, the transport models take into account various effects of the repository: mechanical rock deformation, the presence of seals in shafts and boreholes, and thermal effects on rock and fluids. The models then describe radionuclide movement as affected by chemical retardation and the coupling between solute concentrations in the rock matrix and in fractures; both of these mechanisms may have significant effects on transport. A simplified discussion of the transport models appears in pages 8.3.5.13-56 through 8.3.5.13-80 of the Site Characterization Plan (1). The results obtained from applying the transport models are estimates of the flux of radionuclides across the accessible-environment boundary as a function of time after the repository has been closed.

METHODS FOR PREDICTING SYSTEM PERFORMANCE

The second basic feature of the performance-assessment program is the provision of methods for applying the concepts and models of the system components. These methods must be able to predict performance under the conditions that are expected to occur at the site and under the disturbed conditions that, although unexpected, may occur in the future. Such disturbed conditions may occur as the result of natural events and processes or of human activities. To apply the models, then, requires that the program develop classes of scenarios # hypothetical sequences of possible future events and processes. The methods used in studying each of the three components must be able to assess performance under the assumption that members of these scenario classes have occurred at the site. To provide this assessment capability, the program provides a hierarchy of methods for the analyses of each component, as shown schematically in Fig. 2. At the base of the pyramid in Fig. 2 are the complex models that are most useful in detailed studies of the physical phenomena that may be important to isolating waste. Such models are typically embodied in computer codes that can represent the phenomena in as many as three physical dimensions. Although the complexity of these models allows them to represent coupled interactions and other detailed mechanistic effects, it also precludes their use in statistical studies where many repetitive calculations must be made. An example of these complex methods is NORIA, a two-dimensional code that depicts two-phase, two-component, nonisothermal flow in unsaturated media (3).

The performance assessments also require less complex methods, which Fig. 2 shows as the middle section of a pyramid. These models use the results of the detailed models as input. Among the uses of such models are bounding analyses of the performance of repository subsystems, probabilistic (statistical) as well as deterministic studies, and examinations of the consequences of individual scenarios. An example of these less complex methods is TOSPAC, a one-dimensional code that treats ground-water flow and radionuclide transport under isothermal conditions (4).

Because the regulations governing waste isolation require statistical analyses of radionuclide releases from the entire repository system, another class of methods is needed; Fig. 2 shows them as the least complex of the methods, at the top of the pyramid. These methods are useful in performing bounding analyses of the entire repository system and in combining the effects of scenarios to study compliance with the regulations. An example of

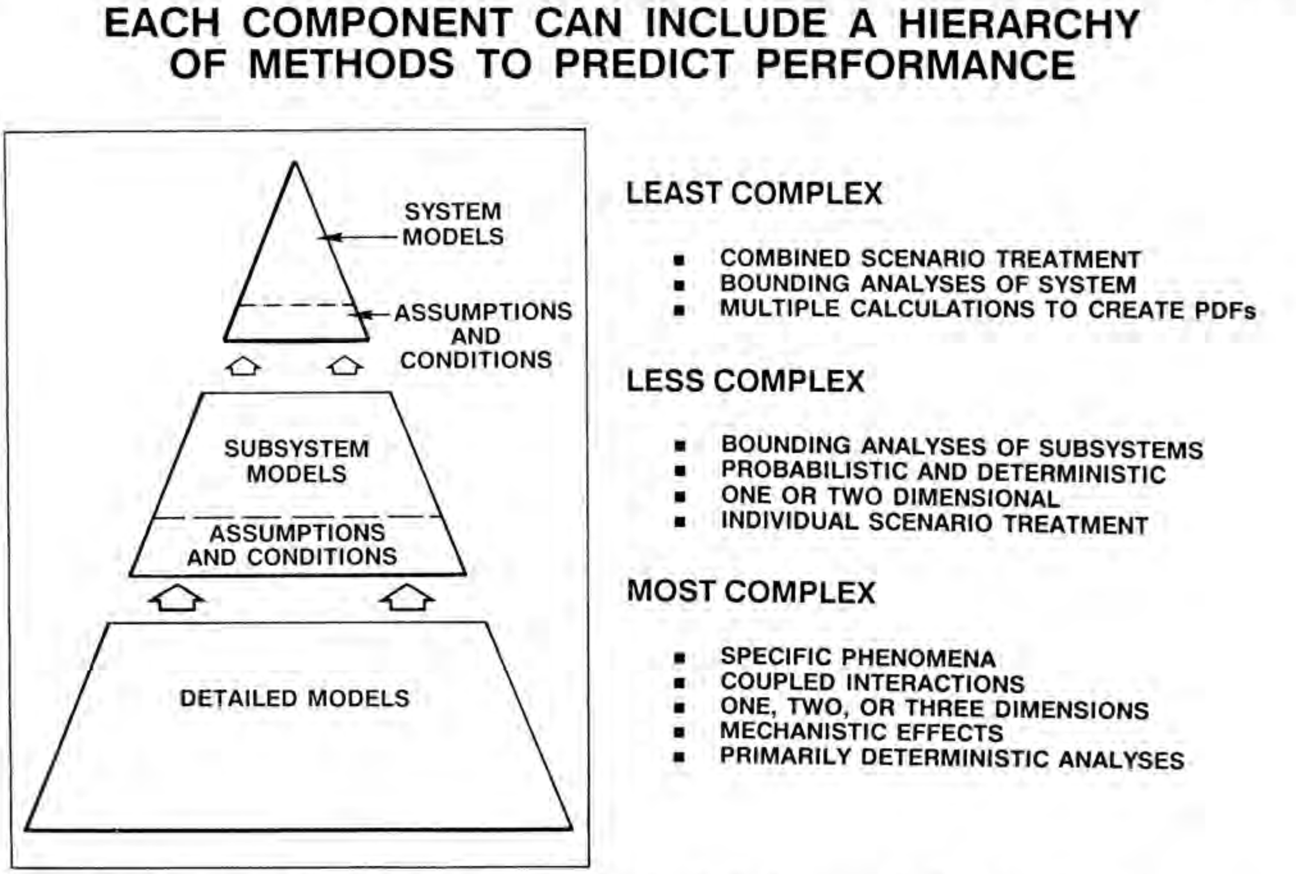

Fig. 2. The Hierarchy of Methods Used for Assessing the Performance of a Repository System.

such a method is the computer code that will simulate the total system for showing compliance with the EPA standard. This code will use Monte Carlo simulation to produce a probability density function describing all radionuclide releases. Such a simulation requires a computer code that models all the important physical phenomena but must nevertheless run quickly because it must be run thousands of times. The simplifying assumptions that must be built into this code and into other codes of its class must be based on studies performed with the more complex methods. As Fig. 2 shows, the more complex classes of methods provide the assumptions and conditions that are the input to the least complex class.

APPLICATIONS

The ultimate application of total-system performance assessment is the evaluation of the suitability of the Yucca Mountain site and the associated licensing process. There are, however, numerous other applications that must be addressed, including some at the current time in the program.

One current application is the role in the definition of the site- characterization program. Many of the tests and data-gathering activities at the Yucca Mountain site will provide information that will be used directly for performance assessment. Consequently, the development of the site- characterization plan included a process to develop the kinds and amounts of information needed to serve as a guide for the development of the testing program. This process will continue as initial information becomes available from site characterization and the test program needs to be refined.

The conduct of the site-characterization program must also use performance- assessment methods to evaluate the impact of testing activities on the integrity of the site itself. Tests and other major activities must be examined to ensure that fluids, materials, or damage to the rock that might result from testing do not have a significant negative impact on the isolation capacity of the site or on the ability to conduct other tests. These examinations are part of the preparation for field activities at the site.

During the site-characterization program, much information will be obtained about the geologic and hydrologic setting at Yucca Mountain. This information will be analyzed to provide interpretation about the nature of the fluid flow in the unsaturated zone. These analyses will, in many cases, use the same calculational methods as will be used for total-system performance assessment. In addition, the validation of these methods will require numerous analyses and comparison with observations. The analyses may reveal a need for additional data, which the site-characterization program can then be redirected to provide.

The design of a repository for the Yucca Mountain site will soon begin another more advanced stage. A more detailed design will be prepared, and design configuration will be established on the basis of new information obtained from site characterization. These design decisions must be based on evaluations of the impact of alternatives on waste isolation. Thus, the methods of postclosure performance assessment must be applied to support the development of the design.

Finally, when the decision on the suitability of the Yucca Mountain site is made and a license application is submitted to the NRC, specific evaluations must be made and supported. Evaluations must be made of the long-term environmental impacts of constructing the repository. Further,

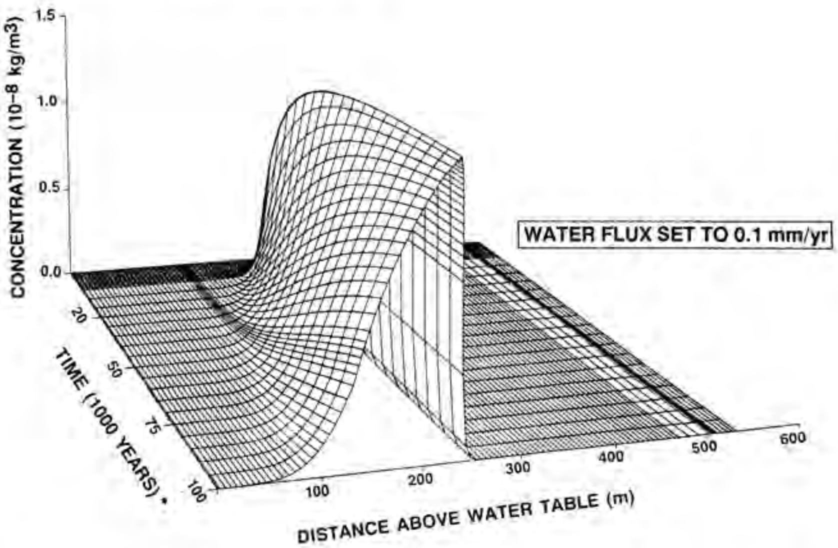

Fig. 3. TOSPAC Calculation of the I-129 Concentration in the Matrix.

specific evaluations to show compliance with regulatory standards must be performed.

These will include individual compliance with each of the performance objectives of 10 CFR 60 and, in particular, the evaluations of the system with respect to the isolation standards of the EPA. Calculations will be made of the amount of each radionuclide that would be transported to the accessible environment. An example of this type of calculation, taken from test runs of the TOSPAC Code (4), is shown in Fig. 3. These will be the ultimate and most important of the applications of the methods used in total-system performance assessment methods. Figure 3. TOSPAC calculation of the I-129 concentration in the matrix.

SUMMARY

The Yucca Mountain Project includes a program to provide total-system performance assessments. This program is an integral part of the activities to evaluate the Yucca Mountain site and has been used to guide the development of site-characterization activities.

Conceptual models have been developed to describe flow and radionuclide transport in the unsaturated zone. These models must be refined to address a comprehensive set of scenarios that describe both expected and disturbed conditions at the site. Because these models are based on initial data and understanding of the site, it is expected that they will be enhanced and modified as more information about the site is obtained during site characterization.

Methods to use conceptual models of the site have likewise been developed but will also be refined during site characterization. These models necessarily include different levels of complexity, ranging from complex methods describing detailed phenomena to more simple methods describing system behavior. These methods must provide deterministic assessment of system performance for a given set of descriptive parameters and statistical assessments that address a wide range of parameter values and uncertainty. Finally, they must accommodate a wide range of scenarios that describe both expected and potential disturbed conditions at the site.

Application of these methods is now primarily in support of the site characterization program but will soon include support for more advanced stages of design and will ultimately emphasize analyses supporting demonstration of environmental compliance and a license application to the NRC.

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